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COMPUTER CONTROLLED MICROWAVE OVEN SYSTEM FOR RAPID WATER CONTENT DETERMINATION

by

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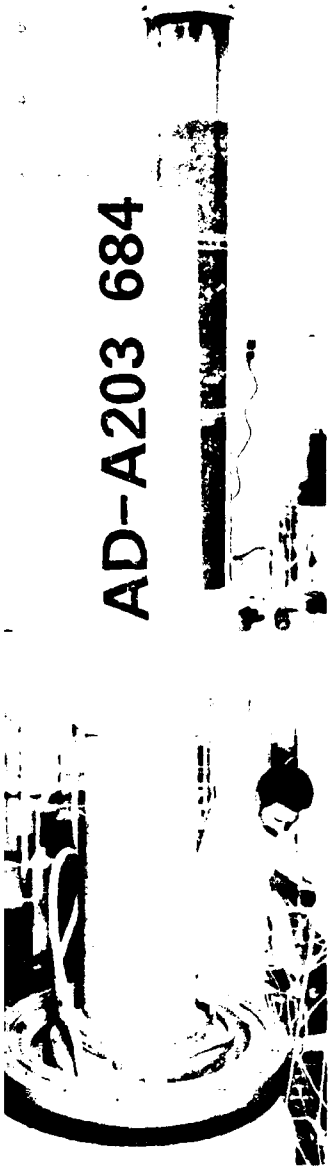

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Equipment for determining water content rapidly, accurately, and reliably is required to properly monitor the compaction of earth fills. If the design of a soil structure is based on one set of behavior characteristics but another set is obtained because of improper compaction control, the result can be a structure with performance and maintenance problems over its entire life. Water content may be determined in the conventional oven but this may require up to 24 hr. Under field conditions where large volumes of earth are being placed, real-time water content information is essential because if 24 hr is required to determine that the water content of a layer is unacceptable, that layer may be buried under several feet of subsequently placed and compacted material.

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A microwave drying system was developed in this investigation to determine water content reliably and accurately in real-time. The design of the system was based on continuously monitoring the weight change of a soil specimen subjected to microwave radiation. An electronic balance was used to monitor weight change in the specimen, and a small computer interfaced with both the balance and a microwave oven in such a manner as to allow software control of the oven in response to specimen water (weight) loss.

Theoretical and practical considerations, as well as the equipment and results, leading to the development of equipment are discussed in the study. Although not strictly equipment, the controlling software is an integral part of the system. A source code of this software is included in the study. A variety of soils were tested in the investigation. Comparison of water content determined in the conventional oven with that determined by the microwave system showed agreement, generally, within a few tenths of a percent. The effects of sample size, material plasticity, and particle size are investigated and discussed in the study.

PREFACE

The study reported herein was sponsored by the US Army Engineer Division, Ohio River (ORD), under IAO No. ORD-87-63 dated 21 May 1987. The investigation was conducted by the US Army Engineer Waterways Experiment Station (WES) during FY 1987 and FY 1988.

The study was conducted under the direction of Dr. W. F. Marcuson III, Chief, Geotechnical Laboratory (GL), and under the general supervision of Mr. G. P. Hale, Chief, Soils Research Center (SRC), and Mr. C. L. McAnear, Chief, Soils Mechanics Division (SMD). The project engineer for the study was Mr. P. A. Gilbert, SRC, SMD. This report was prepared by Mr. Gilbert. Mrs. N. J. Johnson, Information Technology Laboratory, edited this report under the Inter-Governmental Personnel Act. Project monitors for this study were Messrs. D. P. Hammer and J. W. Emmerich, ORD.

COL Dwayne G. Lee, EN, is the Commander and Director of WES. Dr. Robert W. Whalin is the Technical Director.

CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC)
UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic metres
degrees (angle)	0.01745329	radians
Fahrenheit degrees	5/9	Celsius degrees or Kelvins*
inches	2.54	centimetres
ounce (mass)	28.34952	grams

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

COMPUTER CONTROLLED MICROWAVE OVEN SYSTEM FOR RAPID WATER CONTENT DETERMINATION

PART I: INTRODUCTION

Background

1. Compaction characteristics and hence engineering properties of a compacted soil are dominated by the water content of the soil.* Designers of structures built on or with soil depend on stress-strain and strength characteristics determined for a given soil at a specific water content and compactive effort. Deviation from specified conditions can result in a structure which has performance and maintenance problems over its entire life; for this reason, it is imperative that soil water content and compaction requirements (either compactive effort or percent compaction) be continuously and strictly monitored during construction. Part of this monitoring is accomplished by field and laboratory testing. Judging acceptability of the water content of compacted materials is very difficult because of the time element involved. Testing for field water content and both field and laboratory density requires 24 hr for results to be obtained and, because of high placement rates achievable with modern construction equipment, after 24 hr the material being tested is often buried under several feet of subsequently placed and compacted material. This situation forces the use of "quickie" methods for water content determination which are, too often, less accurate than required for proper field earthwork compaction control and places extreme pressure on contractor quality control/quality assurance (CQC/QA) programs.

2. Water content determination in the conventional constant temperature 110° C ± 5° C (230° F ± 9° F)** oven is simple and represents the standard for accuracy. However, because 16 to 24 hr is required to determine water content in the conventional oven, its use in field compaction control is inconvenient, impractical, and could lead to the kind of time-lag problems referred to above.

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* Water content is usually defined as the ratio of the weight of water to the weight of solids in a given mass of soil.

** A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 3.

Expedient Methods of Water Content Determination

3. Several techniques for rapid water content determination have been used in the past, some of which were more accurate than others. Certain of the more widely used methods will be listed and described here for completeness.

a. Soil may be dried in a vessel over an open flame for rapid water content determination. This technique may lead to inaccurate water content because high uncontrolled temperature produced by the flame may drive off adsorbed water and burn or drive off volatile organic material, neither of which is part of a normal water content determination.

b. Water in a soil may be extracted by repeatedly saturating the soil with alcohol then igniting and burning off the alcohol. Sources of error in this technique are basically the same as those in a above.

c. A "Speedy Moisture Tester" kit is commercially available in which water in a subject soil is reacted with calcium carbide to produce acetylene gas in a pressure tight container. Gas pressure which develops in the container is correlated with water content of the soil. Accuracy is a problem with this technique since soils (and especially clays) of different particle sizes bind and hold water at different energy levels, and there is no assurance that calcium carbide will react correctly with bound or adsorbed water. Additionally, accuracy is affected by the presence of organic material in soils under test.

d. Nuclear devices which detect the presence of hydrogen atoms are commercially available and used for rapid water content determination. The accuracy of these instruments is affected by the presence of any hydrogen atom, including those in bound (adsorbed) water and those present in organic material, neither of which should be counted in a (normal) water content determination. Additionally, the accuracy of these devices is affected by the presence of iron, potassium, and chlorine compounds. Other disadvantages of nuclear instruments are:

(1) They are very expensive.

(2) They must be calibrated frequently.

(3) They contain potentially dangerous radioactive material.

e. Microwave ovens have been used for rapid water content determination and several investigations have been performed (Ryley 1969; Gilbert 1974; Lade and Nejadi-Babadai 1974; Charlie, Von Guten, and Doehrmy 1982; Denton 1987) to study the effectiveness of this method or to improve the technique for microwave oven drying. These investigations have shown that the use of a microwave oven is feasible, but some details in the use of the device were not adequately resolved. In the use of a microwave oven for soil drying, as long as soil is exposed to

microwave radiation, energy is applied to the soil specimen and converted into heat. Time of exposure is the only control on the amount of energy applied to the soil by a microwave oven and additional research on time exposure and material response is indicated. Microwave ovens may be used to dry soil in a manner equivalent to that achieved in the conventional oven if energy applied by the oven can be satisfactorily controlled.

Objective and Scope

4. The objective of this study is to develop a microwave oven system to dry soil in a manner equivalent to that achieved in the conventional constant temperature oven. This objective will be achieved by first examining electromagnetic theory to learn how microwaves react with moist soil to produce heat and consequently dry moist soil.

5. A microwave system to dry soil will be described along with a testing program on typical inorganic soils of the type normally used for embankment construction. The results of soil drying tests will be described along with some interpretation of the results.

PART II: THEORY OF MICROWAVE HEATING

Electromagnetic Theory

6. Four vector quantities quantify the state of electric and magnetic fields in an (electrically) isotropic medium acted on by electromagnetic waves. The quantities are (Kraichman 1970, Kraus and Carver 1973):

a. Magnetic flux density $\bar{B}$ (webers/m^2).

b. Electric flux density or displacement $\bar{D}$ (coulombs/m^2).

c. Magnetic field intensity $\bar{H}$ (amps/m).

d. Electric field intensity $\bar{E}$ (volts/m).

These quantities are related through the expressions

$$\bar{D} = \epsilon\bar{E} \tag{1}$$

and

$$\bar{B} = \mu\bar{H} \tag{2}$$

where

ϵ = permittivity or dielectric constant of the medium, farards/m

μ = magnetic permeability of the medium, henrys/m.

One additional expression relating electric field intensity and current density within a medium acted on by electromagnetic waves is necessary for completeness

$$\bar{J} = \sigma\bar{E} \tag{3}$$

where

$\bar{J}$ = current density within the medium acted on by electromagnetic radiation, coulombs/second-m^2

σ = conductivity of the medium, 1/ohm-m

The medium of interest in this study is a soil-water-air mixture. In order to accomplish the objective of the study, it will be necessary to understand the interaction between microwave energy and moist soil sufficiently to develop techniques and equipment to dry soil in a microwave oven to the extent accomplished in a conventional oven. Microwaves are part of the electromagnetic spectrum which is shown in Figure 1. Wavelengths of microwave range from 1 cm

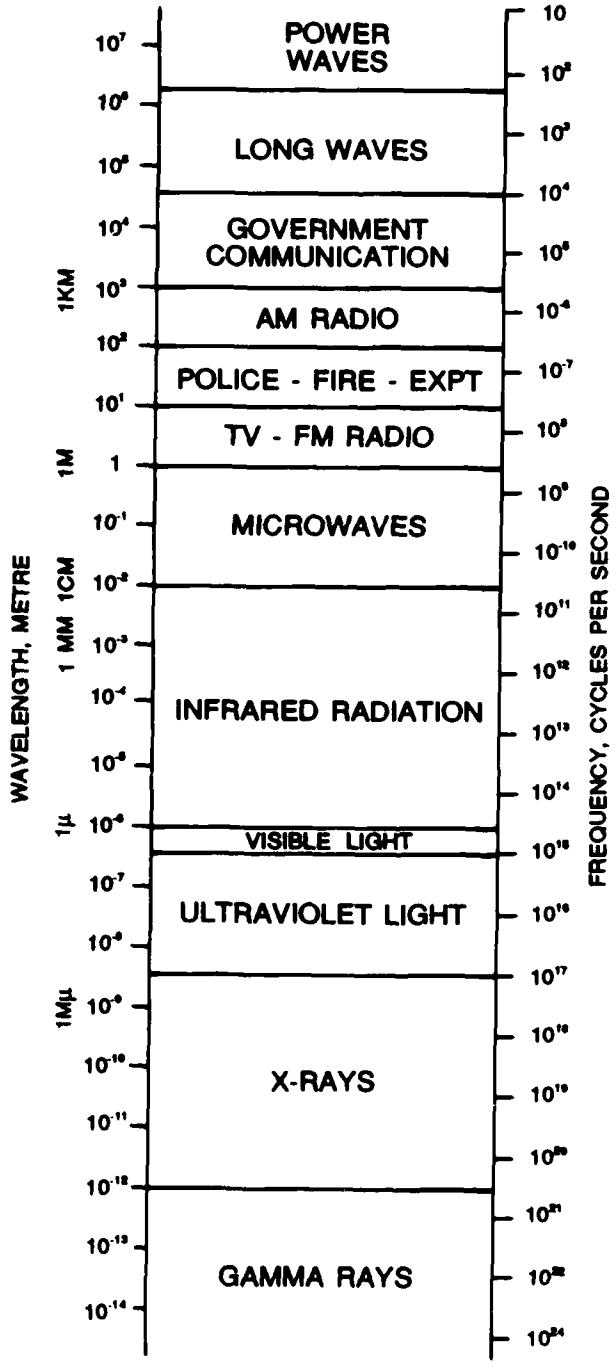

Figure 1. The electromagnetic spectrum

:o 1 m. The frequency of particular interest for this study is 2.45×10^9 cps vith a wavelength of about 12.24 cm.

7. Electromagnetic theory is expressed in four equations given by James Clerk Maxwell around 1860. The equations (expressed in differential form), known as Maxwell's equations are:

$$\bar{\nabla} \times \bar{H} = \bar{J} + \frac{\partial \bar{D}}{\partial t} \tag{4}$$

$$\bar{\nabla} \times \bar{E} = - \frac{\partial \bar{B}}{\partial t} \tag{5}$$

$$\bar{\nabla} \cdot \bar{D} = \rho \tag{6}$$

$$\bar{\nabla} \cdot \bar{B} = 0 \tag{7}$$

where

$\bar{\nabla}$ = the del operator

t = time

ρ = the charge density, coulombs/m^3

8. For fields which vary harmonically with time, as would be the case for those fields inside a microwave oven, Maxwell's equations assume a special form

$$\bar{\nabla} \times \bar{H} = (\sigma + i\omega\epsilon)\bar{E} \tag{8}$$

$$\bar{\nabla} \times \bar{E} = -i\omega\mu\bar{H} \tag{9}$$

$$\bar{\nabla} \cdot \bar{D} = \rho \tag{10}$$

$$\bar{\nabla} \cdot \bar{B} = 0 \tag{11}$$

where

i = the complex number, $\sqrt{-1}$

ω = the harmonic frequency of the field

9. One of the important characteristics of an electromagnetic wave is that it can transport energy. The rate of energy flow per unit area in a plane electromagnetic wave can be determined with a vector $\bar{S}$ called the Poynting vector. The Poynting vector is defined as

$$\bar{S} = \bar{E} \times \bar{H} \tag{12}$$

According to Poynting's theorem, the energy flux flowing into a volume V bounded by a surface with area A is given by the surface integral of the normal component of the Poynting vector. That is

$$\int_A \bar{\nabla} \cdot \bar{S} dA = \int_V \bar{\nabla} \cdot (\bar{E} \times \bar{H}) dV \tag{13}$$

Using the well-known vector identity

$$\bar{\nabla} \cdot (\bar{E} \times \bar{H}) = \bar{H} \cdot (\bar{\nabla} \times \bar{E}) - \bar{E} \cdot (\bar{\nabla} \times \bar{H}) \tag{14}$$

and substituting in Equations 8 and 9, Equation 13 becomes

$$-\int_A \bar{\nabla} \cdot \bar{S} dA = \int_V \sigma \bar{E} \cdot \bar{E} dV + i\omega \left(\int_V \mu \bar{H} \cdot \bar{H} dV + \int_V \varepsilon \bar{E} \cdot \bar{E} dV \right) \tag{15}$$

which may be further simplified to the form

$$-\int_A \bar{\nabla} \cdot \bar{S} dA = \int_V \sigma E^2 dV + \frac{i\omega}{2} \int_V \mu H^2 dV + \frac{i\omega}{2} \int_V \varepsilon E^2 dV \tag{16}$$

This equation suggests that the total power transmitted to a body subjected to electromagnetic waves occurs as the result of three components of energy transfer given by the three terms on the right-hand side of Equation 16. The complex number i on the last two terms in the equation indicates that they lead the first term by 90 deg. Components of heating determined by the equation are, respectively, those due to conductivity, magnetic reaction, and electric displacement. Each will be discussed below.

Conductive Heating

10. The first term of Equation 16 is given by

$$Q_c = \int_V \sigma E^2 dV \tag{16a}$$

where Q_c is the component of heating due to conductivity or ohmic reaction; heating which occurs from this component is directly analogous to heating which occurs in a resistor in an electronic circuit from the dissipation of electrical power in that resistor. Conductivity does not contribute significantly to heating of (usual) soils subjected to microwave energy in a microwave oven because the conductivity σ of most soils is relatively small at microwave frequencies.

11. Lundien (1971) measured the conductivity of several soils with widely varying physical properties and water contents at 1.074 GHz, that is, 1.074 billion cps. These data are summarized in Figure 2 which shows conductivity versus volumetric water content. (Volumetric water content is the ratio of volume of water in a soil specimen to total specimen volume.) The figure shows that conductivity increases as soil type goes from sand to silt to clay and conductivity increases with water content. Additionally, Lundien found that conductivity increases with frequency at a decreasing rate, 1.5 GHz being the highest frequency used in that study.

12. As can be seen from Equation 16a, energy flux due to conductance flowing into a volume acted on by microwave energy is directly related to conductivity σ, the square of the electric field strength E (which is related to output power of the microwave oven in use), and volume V of the test specimen.

13. Conductive heating in microwave oven drying of soils is undesirable in the same sense that "short-circuiting" is undesirable in an electronic circuit. The reason being that neither phenomenon can be very well controlled and will likely result in system damage. Indeed the two phenomena are related in that they are caused by electrical conductivity which is too great (electrical resistance which is too small) for the electrical current level of the system and arcing results in both cases. Water present in a soil increases the conductivity (Figure 2). Therefore, if certain minerals are present in a

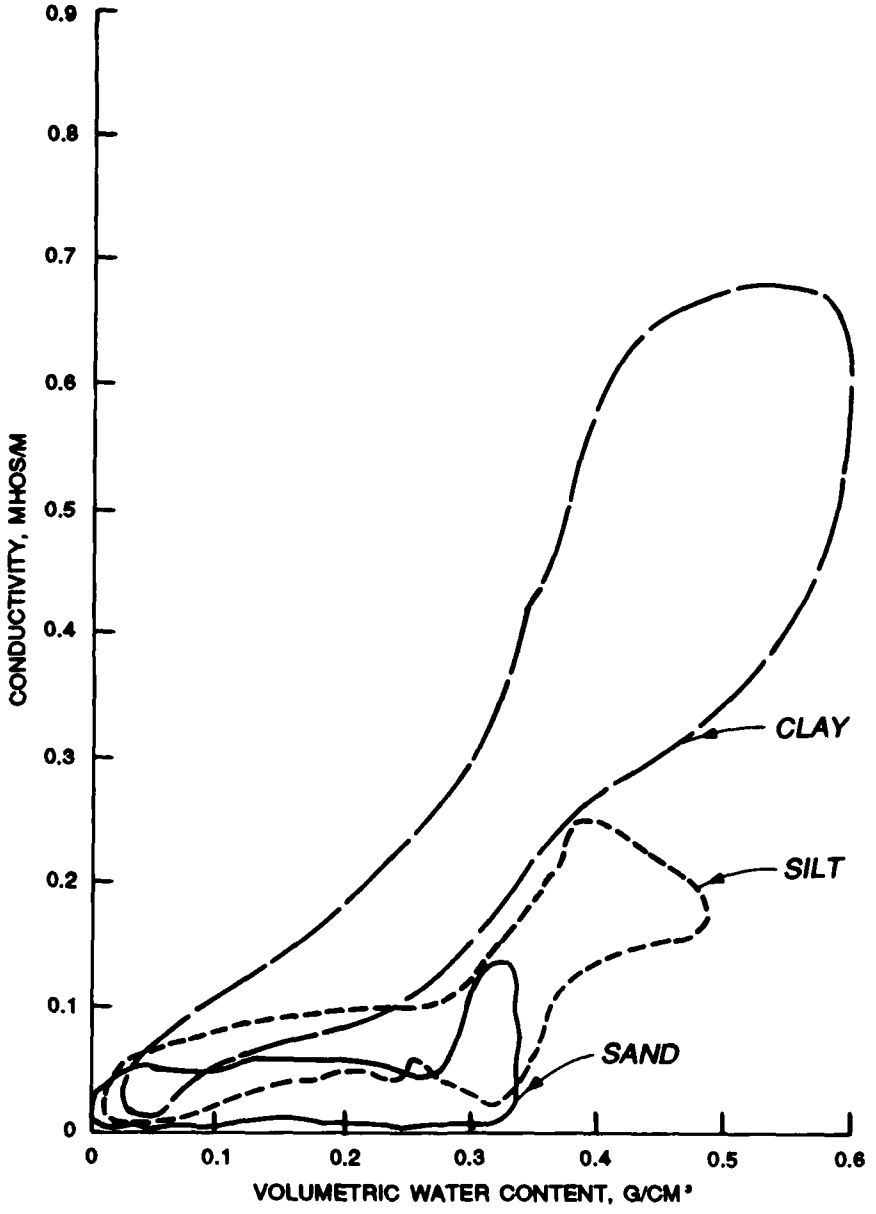

Figure 2. Conductivity versus water content at 1.074 GHz (Lundien 1971)

soil specimen with a high water content which is subjected to microwave energy, arcing could result which might start an exothermic oxidation process causing the soil specimen to burn at high temperature (Gilbert 1974; Kuehn, Brandvig, and Jefferson 1986). Minerals which can cause such problems are those which contain ferrous (Fe++) iron compounds which may react with microwaves and water present to cause a soil specimen to ignite, burn at very high temperature, and lose volatile material (combustible iron compounds) through the combustion process. High temperatures accompanying this process pose the threat of damage to the microwave oven and a safety threat to personnel operating the oven.

Magnetic Reaction

14. The second term of Equation 16 is given by

$$Qm = \frac{i\omega}{2} \int_V \mu H^2 dV \tag{16b}$$

where Qm is the component of heating due to the reaction of soil with the magnetic field present in electromagnetic waves. Heat produced by this component (as seen from Equation 16b) varies directly as the harmonic wave frequency ω, the square of the magnetic field strength H (which is a function of oven output power), volume V of the specimen under test, and magnetic permeability μ of the substance exposed to the field. Magnetic permeability is given by the equation

$$\mu = \mu_r \mu_o \tag{17}$$

where

μ_r = relative permeability of the subject material (dimensionless)

μ_o = magnetic permeability of a vacuum, $4\pi \times 10^{-7}$ henrys/m

Table 1 shows relative permeability of different materials. Most soils are nonmagnetic, having a relative permeability of about unity; therefore, the component of heating due to reaction to the magnetic field is not a significant part of total heating which results from exposure to microwave energy. Heating due to magnetic field reaction is significant only for material with an appropriately large magnetic permeability. To confirm this, two empty

metal vessels of the same physical size (volume) were subjected to microwave energy in a microwave oven for 60 sec. One vessel was of aluminum and the other of steel. The aluminum vessel heated up slightly from room temperature (about 75° F (23.8° C)) to approximately 80° F (26.6° C), whereas the steel vessel heated up to about 110° F (43.3° C). For these two materials, there was no substantial difference in either conductivity or dielectric constant; however, the relative permeability of aluminum was about 1, whereas the value for mild steel was about 2,000. This suggests that magnetic heating in materials exposed to microwaves may be significant for those materials with sufficiently high magnetic permeability, and this may include soils with high concentrations of ferromagnetic minerals.

15. Heat produced in susceptible (ferromagnetic) material subjected to a magnetic field is directly related to magnetic hysteresis of the material. If magnetic field intensity H increases and decreases harmonically so that the magnetization of a substance within the field repeatedly traces out a hysteresis loop (as seen in Figure 3), the area enclosed in this loop represents energy per unit volume expended in the magnetization-demagnetization process in one cycle. In going around the hysteresis loop, energy proportional to the area of the loop is lost; this energy stressing the crystal fragments of the test specimen is consumed and appears as heat. Each cycle contributes to heat

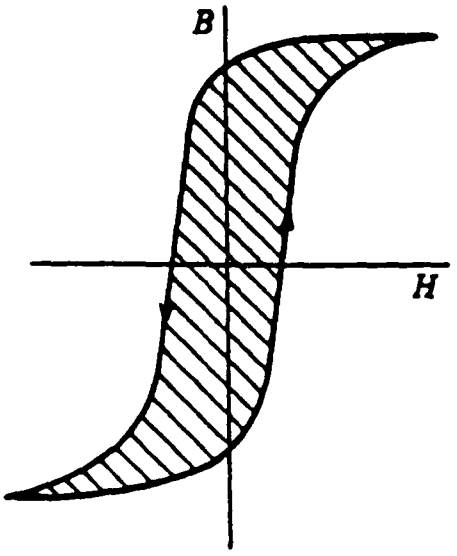

Figure 3. Magnetic hysteresis loop (from Kraus and Carver 1973)

buildup in the specimen. The area of the hysteresis loop is determined by magnetic permeability of that material acted on by the field. Materials with sufficiently low magnetic permeability will not be heated significantly by this component of microwave energy transfer.

Displacement Heating

16. The third term of Equation 16 is given by

$$Q_D = \frac{i\omega}{2} \int_V \varepsilon E^2 dV \tag{16c}$$

where Q_D is the component of heating due to electric displacement. This is the component which is most significant in heating materials normally placed in a microwave oven. Heat produced by this component (as seen from Equation 16c) varies directly with harmonic wave frequency ω, the square of the electric field intensity E (which again is a function of oven output power), volume V of the specimen, and permittivity or dielectric constant ε of the substance exposed to the field. Dielectric constant is given in equation form by

$$\varepsilon = \varepsilon_r \varepsilon_o \tag{18}$$

where

ε_r = relative dielectric constant of the subject material (dimensionless)

ε_o = dielectric constant of free space, $\approx 8.85 \times 10^{-12}$ farads/m

Table 2 shows relative dielectric constant of different materials.

17. It is seen from the table that water has a high dielectric constant compared with most common materials. This means that water will absorb microwave energy and convert it into heat more efficiently than most materials. Since food is predominantly water, microwave energy will heat food very effectively, especially since the water content of food heated with microwaves does not change appreciably during exposure.

18. However, the process for determining water content of a moist soil in a microwave oven differs considerably from that of heating/cooking food.

Food absorbs energy at constant (or nearly constant) water content in a microwave oven. The purpose of microwave cooking is never to (deliberately) dry food out. Conversely, soil water content determination in a microwave oven requires that the water content change during heating from that of moist soil to that of (conventional oven) dry soil. Energy absorption associated with microwave drying is influenced most significantly by dielectric constant ϵ of the mixture.

19. The dielectric constant of a soil-water mixture varies with water content. This was shown by Lundien (1971), who performed tests on a wide variety of soils over a broad range of water contents. Lundien showed that soils typically have low relative dielectric constant (about 3) at zero volumetric water content, but the value increased smoothly and uniformly to about 80 for a pure water specimen. Frequencies used by Lundien were between 1 and 1.5 GHz, and the relationship between relative dielectric constant and (volumetric) water content is shown in Figure 4 which includes all soils tested at a frequency of 1.5 GHz. Relative dielectric constant for all frequencies used by Lundien is correlated with volumetric water content W reasonably well by the expression

$$\epsilon_r = 40W - 3.9 + (1{,}600W^2 - 392W + 44.81)^{1/2} \qquad (19)*$$

20. Grim (1968) presents data to show that relative dielectric constant of certain clay minerals decreases as temperature and frequency increase. The relative dielectric constant of kaolinite at 1.4 GHz and 140° C is 4.79. The relative dielectric constants of halloysite and montmorillonite at 140° C and 2.5 GHz are 6.9 and 4.7, respectively. These values appear to be roughly consistent with those determined by Lundien.

21. Finally, relative dielectric constant of water is 88 at 0° C and is 55.3 at 100° C (Hodgman, West, and Selby 1958) with a roughly linear variation existing between these limits.

22. The conclusion drawn from the discussion above is that microwave oven water content determination of a soil water mixture is a complex process involving soil mineralogy, water content, and temperature of the resulting mixture as well as frequency and power level of the microwave radiation to

* This expression is an algebraic rearrangement of the Lundien equation. It is, however, mathematically identical to the original equation.

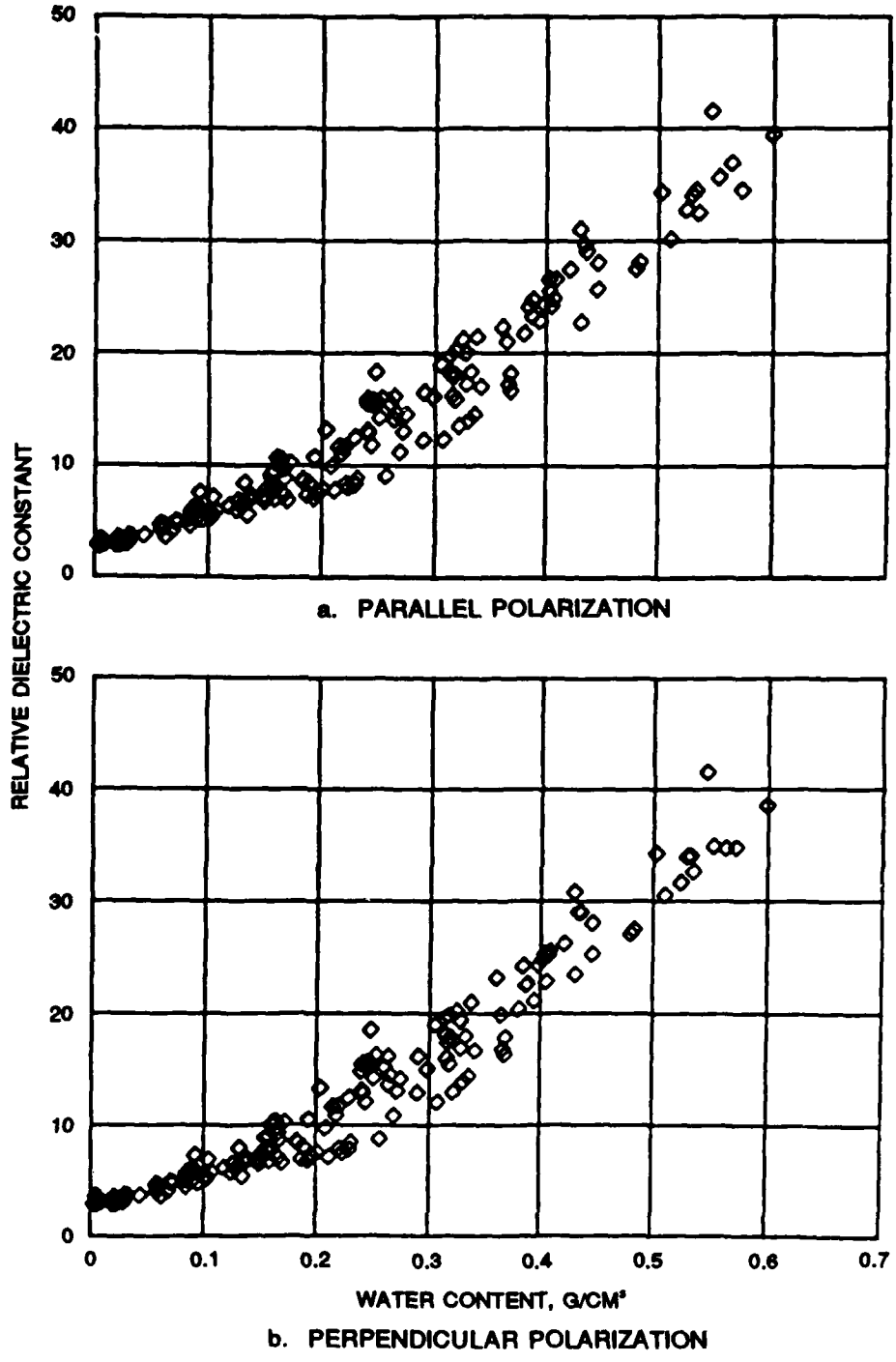

Figure 4. Relative dielectric constant versus water content (from Lundien 1971)

which the mixture is subjected. The implication is that although Equation 16 does not lend itself well to exact mathematical evaluation, the equation is very useful in that it assembles and identifies all of the parameters constituting the problem.

PART III: MICROWAVE HEATING OF SOILS

Heating Mechanism

23. Classical electromagnetic theory correctly identifies pertinent parameters and quantifies heat produced in a body exposed to microwaves on a macroscopic level; it fails, however, to explain the phenomenon at the molecular level. Very basically, heat in a body is the total potential and kinetic energy contained in the molecules of that body. Microwaves heat a body by increasing the molecular kinetic energy of that body. Water is a material particularly susceptible to having its molecular activity increased from exposure to an electromagnetic field because water molecules are dipolar; that is, the center of the positive and negative charges of the molecule do not coincide (Grim 1968). In the presence of a harmonic electric field, dipole molecules tend to rotate to align themselves with the field. However, molecules cannot respond to the field with instantaneous rotation because of inertia and other forces which resist molecular movement, such as internal friction of the surrounding medium. Therefore, the response of water molecules to an oscillating electric field is in many respects similar to the response of a viscously damped mechanical spring-mass system excited by a harmonic force. The electric field frequency desired and the one which produces the greatest amount of heat in the molecular medium is one analogous to the forcing frequency producing resonance in the analogous mechanical system. For example, if the frequency of the electric field is too low, molecular response time is shorter than the time required for the field to change direction. Rotation remains in phase with the field and only a small amount of energy is converted to heat. If, on the other hand, the frequency of the electric field is too high, molecular response time is greater than the time required for the field to change direction, and consequently molecules cannot rotate and no heat is produced. Just as maximum displacement occurs in a mechanical spring-mass system at resonant frequency, there is an optimum harmonic electric field frequency which will cause maximum molecular rotation in a dipolar material. The resulting constant and rapid molecular rotation causes temperature to rise due to the increase in kinetic energy. Heat produced in this manner occurs simultaneously in a body at the surface and to some depth which the microwaves are able to effectively penetrate. Penetration depth, to be discussed later, is

influenced by the electrical characteristics of the material subjected to the field of radiation as well as power and frequency of electromagnetic radiation applied.

24. The harmonic frequency of electromagnetic waves used in most commercially available microwave ovens is 2.45 GHz. This frequency is one of practical choice for commercial ovens because of its optimum balance between efficient heating and maximum penetration depth in food.

Depth of Penetration

25. As microwave radiation penetrates the material of a body, power is lost to each successive layer of that material so that less power is available for heating the interior of that body. This is an important concept since the primary purpose of microwave heating/cooking is to heat a body quickly, and this is accomplished by applying energy to all points in a body (nearly) simultaneously. Therefore, effective depth of penetration is a matter for concern since if the body to be heated is too large, distance from the surface may be so great for such a significant volume of the body that the interior cannot be effectively heated because of power attenuation.

26. Microwave theory (Kraichman 1970) suggests that power level in a body subjected to microwave radiation decays exponentially with distance but never fully reaches a power level of zero. Power is attenuated at a given number of decibels per unit length of material (the number of decibels per length lost depending on the material) and for approximately every 3 db lost, power level is halved. Lord, Koerner, and Reif (1979) investigated attenuation in soils at different frequencies and water contents. For example, Figure 5 is taken directly from the 1979 investigation and shows attenuation at 2 GHz determined for a sand, a silt, and a clay at different volumetric water contents. It is seen from the figure that attenuation increases with water content. If a mixture of the subject sand, silt, and clay at 15-percent volumetric water content (which would be equal to 10-percent water content by weight for a soil with a 1.5-g/cm^3 density) were determined to have an attenuation of 50 db/m, and if such a soil were subjected to microwave radiation at 2 GHz then microwave energy would penetrate this material to a depth of approximately 2.4 in. (6.0 cm) before power level is halved (decreased by 3 db).

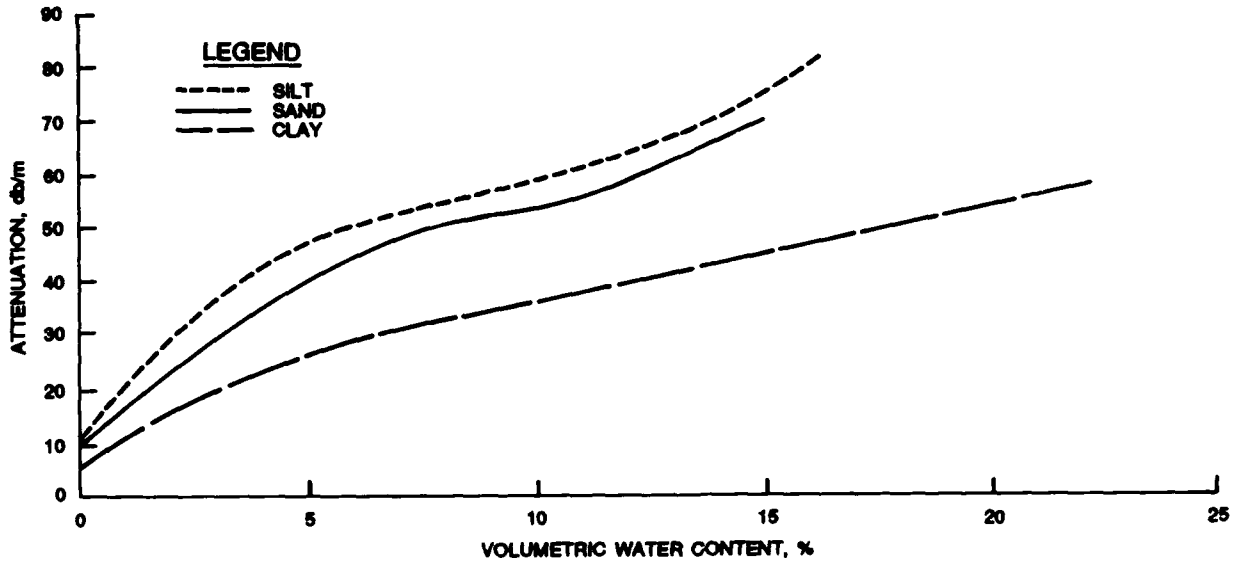

Figure 5. Attenuation versus volumetric water content at 2 GHz (from Lord, Koerner, and Reif 1979)

27. The preceding discussion means, of course, that bodies heated with microwaves do not heat as quickly in the interior as they do at the surface, and high water content slows down microwave heating even further. The suggestion is that soils with high water content are heated and dried at the surface first. Only when the surface of a thick, wet soil mass has been dried somewhat can microwave energy penetrate into the interior for effective drying.

Soil Drying Process

28. The process of drying soil in a microwave oven requires that a soil-water mixture absorb microwave energy. Absorbed energy increases the temperature of the mixture from ambient to the boiling point of water where additional energy absorption vaporizes water present at a constant temperature of 100° C. When all free water in the mixture has been vaporized, the remaining soil and adsorbed water continue to absorb energy and begin to increase in temperature. This process was demonstrated by Gilbert (1974), who measured the temperature of a soil-water mixture with time exposure to microwaves. Typical results are shown in Figure 6. As suggested by examination of Equation 16, microwave heating consists of three components: heating by conduction, magnetic reaction, and displacement. Displacement or dielectric heating accounts for most of the heat energy applied by the microwaves since water has

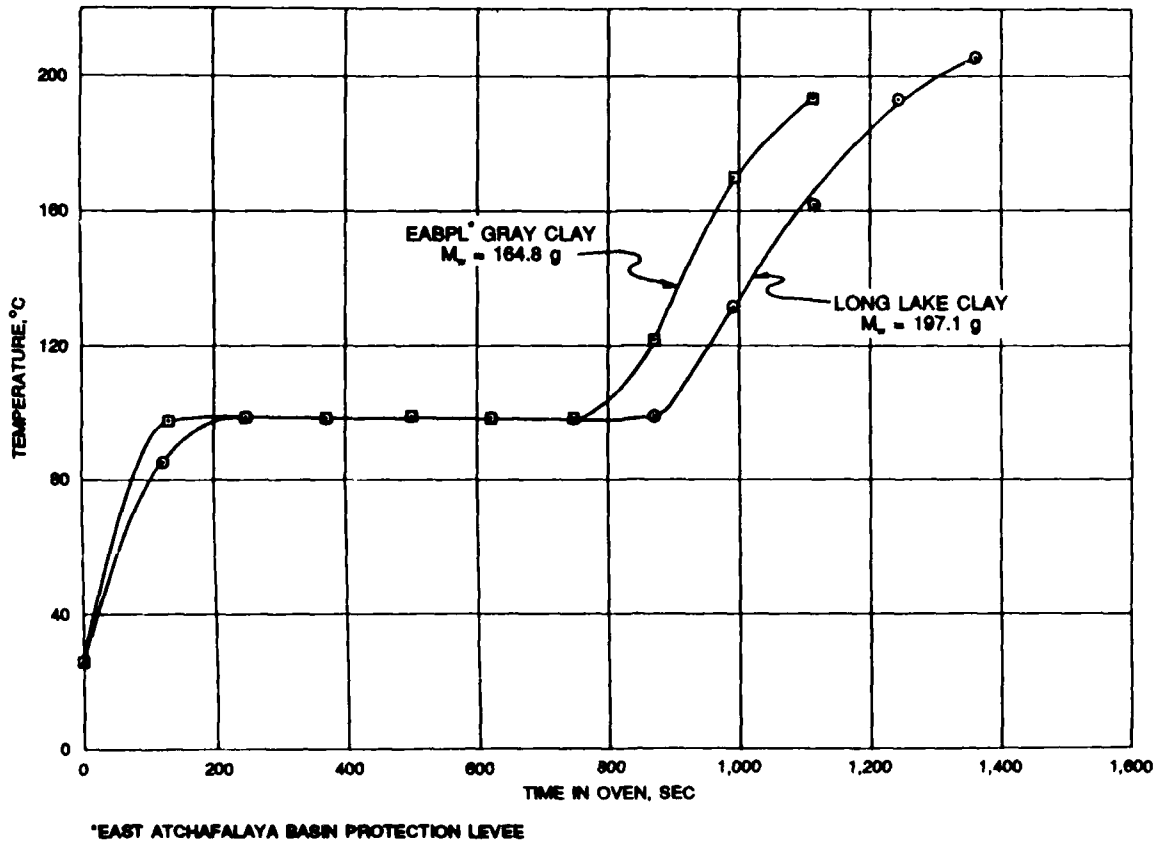

Figure 6. Drying time versus temperature of the soil-water mixture (from Gilbert 1974)

an initially large dielectric constant and converts microwave energy to heat effectively. However, Grim (1968) and Figure 4 suggest that dielectric constant and therefore the capacity to convert microwave energy to heat decrease to a small residual value as greater and greater quantities of water are lost but never to zero. Therefore, "dry" soil possesses a minimal but finite capacity to absorb microwave energy and produce heat due to electrical displacement. The same is true for the conductive and magnetic components given by Equations 16a and 16b, respectively. Conductivity and magnetic permeability of dry soil are both small but nonzero. Therefore, all three of these residual components will allow continued power absorption in soil specimens after the vaporization of all free (absorbed) water present. Continuous power absorption will mean continuous temperature increase as can be seen from temperature increases above 100° C in Figure 6. Continuous and unlimited temperature rise is undesirable in microwave soil drying because a soil specimen exposed to a field of microwave radiation for too long a time period could

overheat, drive off adsorbed water (which is not usually a part of that water removed in water content determination), and because of excessively high temperature which may develop, pose a safety threat.

29. Complicating factors which must be considered in a drying process like that proposed are that if certain minerals are present in soils, they may react with microwaves to very quickly produce dangerously high temperatures in the absence of water; additionally, arcing which will severely damage the oven may also occur in the absence of a water load. Therefore, microwave ovens should not be operated for any extended period in the absence of a load. The use of a microwave oven to dry soil is considered abusive by some manufacturers to the extent that the warranty is voided if the oven is so used. The magnetron in a microwave oven is a radar tube which was designed to radiate into the atmosphere, which is a body with the capacity to effectively absorb an infinite amount of energy. However, in microwave oven use, a magnetron is required to radiate into a small volume enclosed by a metal box, which in itself is an abusive application because energy feedback toward the magnetron would likely cause damage in the absence of a load to absorb energy. Food/water normally present in a microwave oven provides a load for radiated energy and prevents magnetron damage. However, during microwave oven drying of soil, load provided by a soil-water mixture, although initially adequate, diminishes with time to a vanishingly small level as water is vaporized and lost from the system. Radiation into the small metal cavity of low energy absorbing capacity then constitutes abuse, especially if it continues for an extended period. For this reason, the oven used in the present study was provided with an empty oven load which was always present. The empty oven load diminishes effective power radiated by the oven but is a necessary safety feature to prevent oven damage.

30. Continuous time exposure of a soil-water mixture to a field of microwave radiation will result in two easily observed changes:

a. Temperature of the soil-water mixture will increase to the boiling point of water, remain at that temperature until all water is vaporized, and then increase to some higher level.

b. Weight of the mixture will decrease (as the result of water loss), slowly at first, then more rapidly until finally the rate of weight decrease will diminish and specimen weight will converge to a terminal value. It will be shown later that it is advantageous to express this weight change in terms of water content change.

31. Both of these effects are shown in Figure 7. Either of these effects could be used to trigger an automated servo-system to terminate microwave drying. The construction of such a system is the object of this study, and it was determined to trigger the system based on water content convergence rather than specimen temperature rise for three reasons:

a. Temperature triggering would require a thermal probe which might, by chance, be installed in the specimen in a hot spot, a cold spot, or a void. In either of these cases, the probe would measure local atypical temperature behavior and the process would not trigger properly.

b. The terminal temperature of a specimen is not the same for all soil types as can be seen in Figure 7.

c. A triggering mechanism based on weight change in a specimen would reflect a much more average condition within the specimen, and weight change can be measured with greater certainty than temperature change.

Cohesive Soils Subjected to Microwave Drying

32. The behavior of all soil is influenced by the presence of water, but the behavior of cohesive soils or clays is almost completely dominated by the amount of water with which they are mixed. For example, the behavior of a cohesive soil goes from that of a liquid which is unable to sustain static shear stress at water contents above the liquid limit to a plastic solid which shears continuously when a certain threshold shear stress is exceeded at water contents between the liquid and plastic limits, to a brittle solid at water contents below the plastic limit.

33. The surfaces of clay crystals are highly charged and consequently attract and hold (polar) water molecules tightly. These attractive forces, however, decrease as distance from the (crystal) surface increases. Depending on the clay mineral in question, many layers of water molecules may be adsorbed by these attractive forces with energy required to remove adsorbed layers increasing rapidly as distance from the crystal surface decreases (Scott 1963). Different clay minerals differ in size, character, and propensity to retain adsorbed water. This is shown effectively by considering the dehydration curves of Figure 8. These curves show the tendency for continued water loss at temperatures above 100° C, with higher temperatures representing higher energy levels available for water removal.

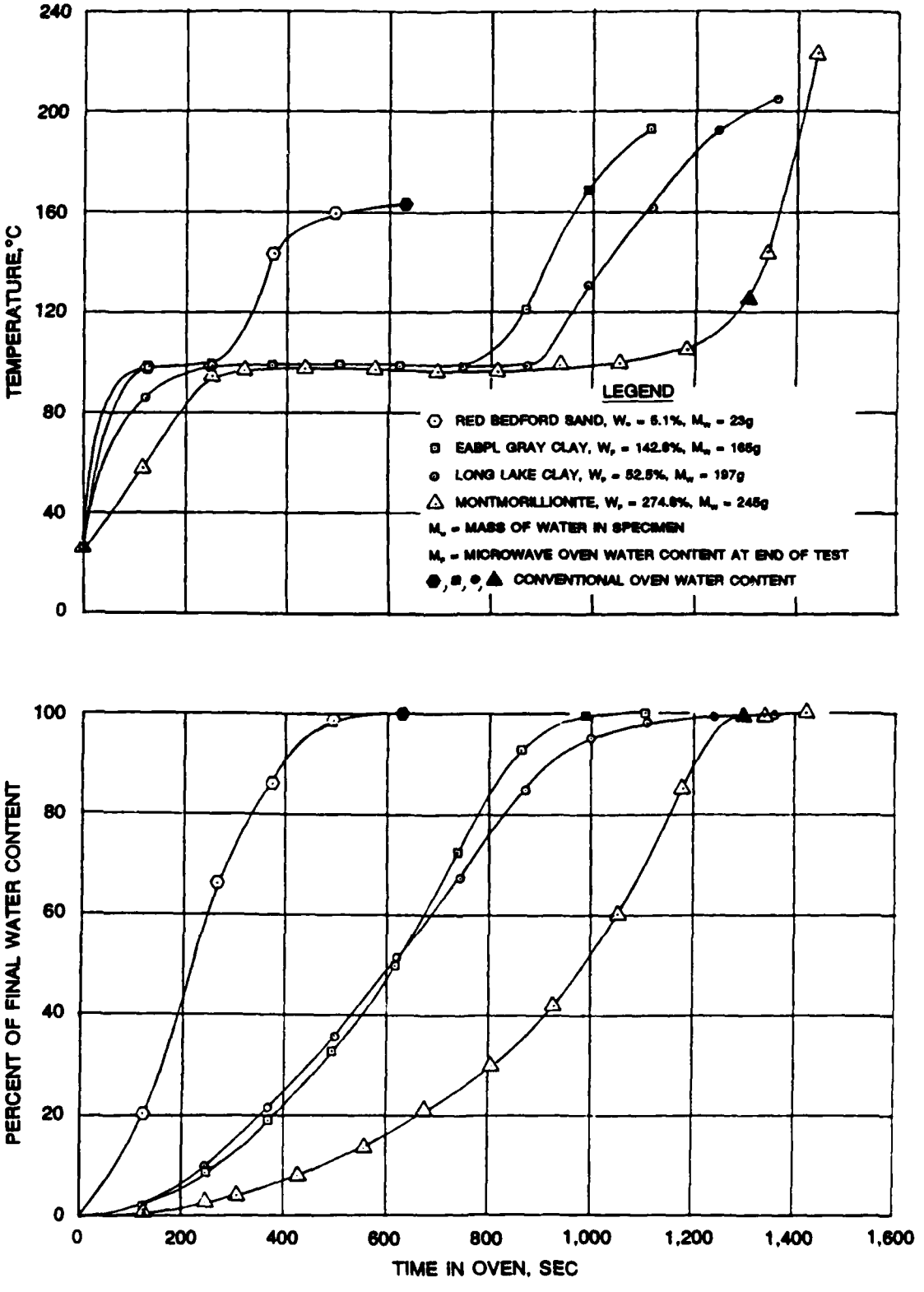

Figure 7. Water content and temperature versus time in microwave oven (from Gilbert 1974)

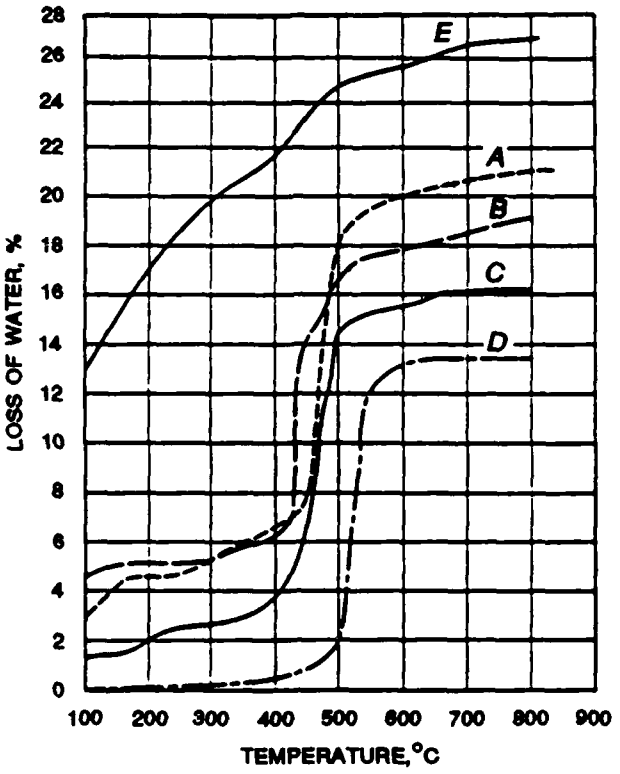

Figure 8. Dehydration curves (Grim 1968) A = halloysite, Liége, Belgium; B = halloysite, Adams County, OH; C = halloysite, Hickory, NC; D = kaolinite, Ione, CA; E = allophane, Moorefield, KY

34. Several theories have been advanced regarding the properties of water in close proximity to clay crystals. For example, it has been surmised (Scott 1963) that because of the spacing and/or structure of the water molecules near the surface of a clay crystal, adsorbed water has properties different from "normal" water and may be solid like ice or possess very high viscosity. Adsorbed water at greater distances from the surface behaves more like "normal" water. Whatever its structure, this water is considered to affect behavior of clay particles when subjected to external stress since adsorbed water comes between the particle surfaces and, depending on thickness of the adsorbed layer, dictates the liquid, plastic, or brittle behavior as described above. To drive off all adsorbed water (as suggested by Figure 8), clay particles must be heated to temperatures well in excess of 100° C, which indicates that the bond between water molecules and clay crystal surfaces is considerably greater than that between "normal" water molecules.

35. In fact, the suggestion of Figure 8 is that the amount of water removed from various clay soils is a function of temperature (or applied energy level). In this sense, there is no unique water content in that removal of water from the proximity of clay crystals requires a variable and increasing expenditure of energy with increasing water removal. Therefore, in concept, water content determination is a complex, nonlinear statistical thermodynamic process, although in practice it is a simple arbitrary mechanical procedure whose value is uniquely specified (statistically) if an arbitrary energy level (temperature) is selected. For example, the concept of water content is quite meaningful and well defined if it is universally agreed to base the procedure on drying a soil-water mixture to a constant weight in an oven maintained at a constant temperature of, say, 110° C. Constant temperature ensures a constant energy level which limits the amount of power a soil mixture can absorb and therefore the amount of water which can be expelled.

36. By contrast, power absorption by a soil subjected to continuous microwave energy is not bounded. If power is continuously applied, it will be converted to heat, and the temperature of a soil-water mixture could theoretically increase without limit. At very elevated temperatures in soil-water mixtures, there is (among other undesirable consequences) the danger of determining an incorrect water content. Figure 7 shows the typical relationship between water content and temperature change with time exposure to microwave energy. It is seen from this figure that as the equivalent conventional oven water content is approached, change in water content with time becomes smaller but temperature of the soil-water mixture begins to increase substantially, especially for highly plastic clays. This is consistent with the argument that energy required to remove water from clay increases with water removal at temperatures above 100° C. This fact is also evident from dehydration curves shown in Figure 8. Since microwave oven heating causes temperature levels in soil specimens to increase in some instances to over 200° C, some overdrying is to be expected, and this may be especially true of clay minerals with a propensity to retain large quantities of adsorbed water. Table 3 shows change in water content of some clay minerals as they are heated from 100° to 200° C and demonstrates that some materials are more susceptible to overdrying than others. This fact was alluded to in American Society for Testing and Materials (ASTM 1988) Standard D-4643 for microwave drying, when it was stated that

the method described in that standard may not yield reliable water content values for soils containing significant amounts of halloysite, mica, montmorillonite, gypsum, or other hydrated materials and highly organic soils. Gypsum-rich soils are included in this group because water contained in the crystalline structure of gypsum is improperly removed in a normal (110° C) water content determination. Water content of such soils should be determined in a 60° C oven, and it may be difficult to determine an accurate water content of gypsum-rich soils in a microwave oven since Ryley (1969) observed that gypsum decomposed and dehydrated under microwave heating. For reference, the dehydration curve of a gypsum-rich silty sand (US Army Engineer Waterways Experiment Station 1954) is shown in Figure 9.

37. Figure 9 demonstrates that if this particular material is inadvertently heated to 150° C (as may be the case with microwave drying), an error of as much as 20 percentage points of water content may result. An error of 20 percentage points in a water content determination is clearly unacceptable. On the other hand, examination of Table 3 reveals that if the drying temperature of many of the clay minerals tabulated can be held to less than 150° C, the change (error) in water content from the 100° C level is tolerably small. However, error increases substantially for most clay minerals if the mixture is allowed to reach 200° C. This suggests that one of the requirements for microwave drying should be the adoption of procedures to help ensure that drying temperature of a soil-water mixture in a microwave oven does not rise to excessive levels.

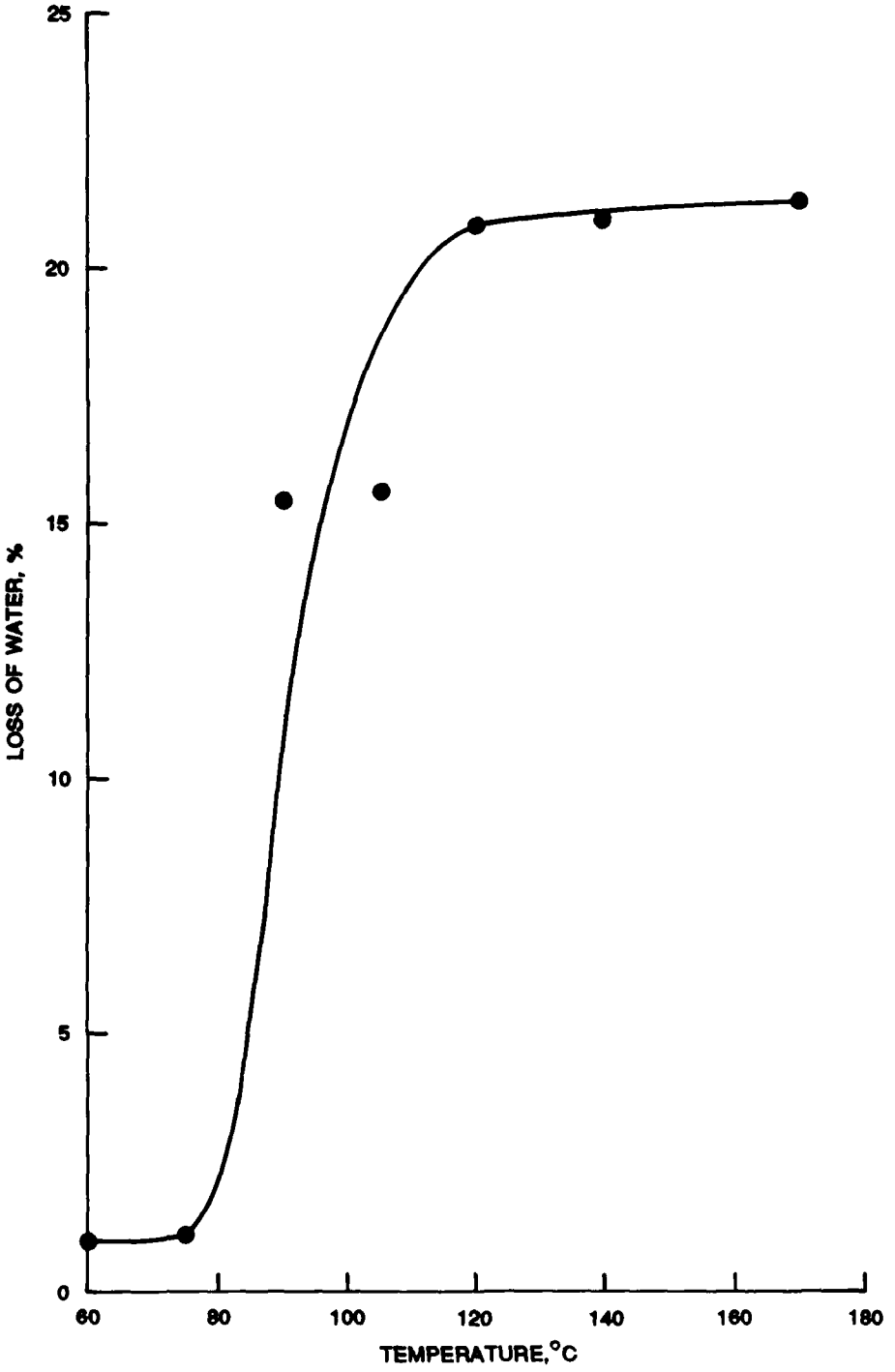

Figure 9. Dehydration curve of a gypsum-rich silty sand

PART IV: EQUIPMENT AND OPERATION

System Overview

38. Equipment to effect controlled microwave drying consists of a constant power output microwave oven, an electronic balance with a RS232C interface, and a small (64 kilobit) microcomputer as well as other miscellaneous small components and software. The equipment is shown schematically in Figure 10. The theory of operation is simply that the soil specimen is weighed continuously while it is microwave heated; the computer monitors the weight change versus time relationship and terminates the process when certain preprogrammed conditions are met.

39. A typical water content versus time relationship for the microwave drying process is shown in Figure 11 (see also Figure 7). Three distinct stages of drying may be identified from the Figure 11. The first is where temperature of the mixture is increased from the ambient level, but this phase is accompanied by little water content change. The second is a stage of maximum rate of weight loss at a constant temperature (100° C) in which water content change is greatest. The third stage is one of decreasing rate of weight loss and one which will be used to trigger process termination. The computer continuously monitors weight loss and time and when the slope of the weight (water content) versus time relationship becomes less than or equal to a certain prescribed value, the process is stopped.

40. Each component of the system will be described separately below.

Microwave Oven

41. The microwave oven used in this study was a Sears Kenmore Model 88961, which was purchased for approximately $330 in mid-1987. Technical specifications furnished by the manufacturer are:

a. Exterior dimensions: 24 in. wide by 15-3/4 in. high by 20-5/8 in. deep.

b. Interior dimensions: 15 in. wide by 9-1/2 in. high by 16 in. deep.

c. Oven cavity size: 1.4 cu ft.

d. Power source: 120-v AC single phase, 14.5 amps, 60 Hz.

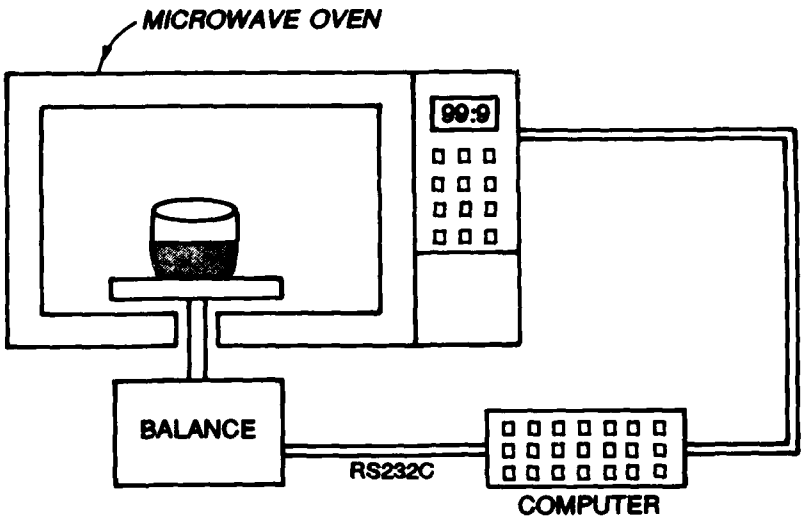

Figure 10. Schematic of microwave drying system

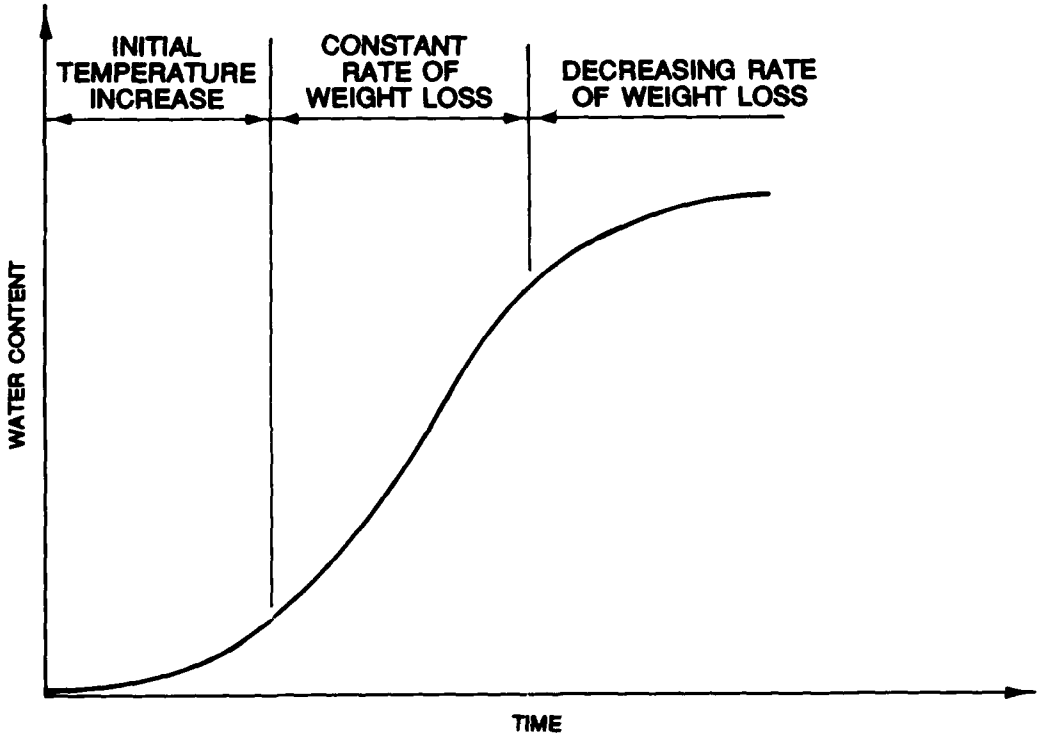

Figure 11. Typical water content/time relationship for microwave heated soil specimens

e. Input power: 1,400 w (±10 percent).

f. Maximum output power: 700 w (+13 percent, -8 percent).

g. Output frequency: 2,450 MHz (2,450,000,000 Hz).

The microwave oven was calibrated during this investigation for useful power using water as the calibration load. Varying masses of water inside insulated containers were subjected to microwave energy for specific time intervals, and the resulting change in temperature was measured and recorded. With this information, the useful output power of the oven at various (water) loads was computed from the equation

$$P = \frac{M \, \Delta T \, C_w}{\Delta t} 4.186 \qquad (20)$$

where

P = output power, w

M = mass of water, g

ΔT = change in temperature of water, °C

C_w = specific heat of water $\approx 1 \frac{cal}{g°C}$

Δt = time interval, sec

units constant = $4.186 \frac{w}{cal}$

The relationship between output power and load in grams of water is shown in Figure 12. This figure shows that oven power is a function of oven load.

42. Additional features of the oven used in this study include a digital membrane control panel which allows programming of cooking time intervals and fractional power settings. Oven power output can be set from 0 to 100 percent of maximum oven power. The magnetron, of course, either delivers 100- or 0-percent power. Fractional power settings are achieved by programming the magnetron to deliver 100-percent power for a desired fraction of a specified time interval. For example, if 50-percent power is desired, the magnetron will output full power 50 percent of the time over the specified interval. The maximum time which can be programmed is about 100 min. At the end of any programmed time interval, an alarm tone sounds for 2 sec.

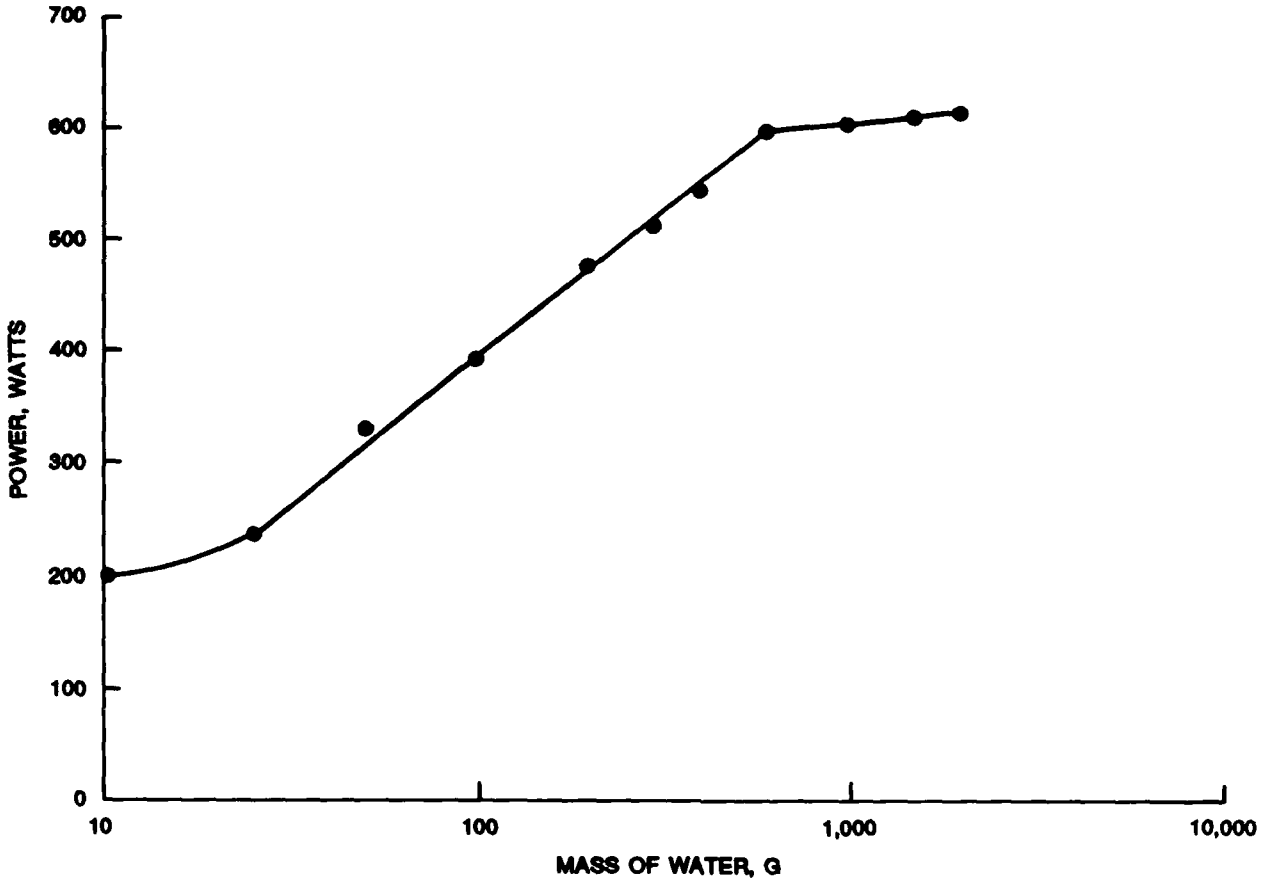

Figure 12. Power calibration of microwave oven

Balance

43. The electronic balance selected for this study was equipped with an optional RS232C serial communications port, which allows direct communication with a computer and results in a system with good noise immunity. The balance can be controlled via the RS232C link and can transmit both status information and data in response to computer commands. Upon command from the computer, the balance is powered up, zeroed, and placed in measurement condition in which data consisting of the current reading on the balance is sent to the computer over the RS232C serial link.

44. The balance was manufactured by A&D Engineering, Inc., of Milpitas, California, and along with the optional RS232C interface cost approximately $760 in mid-1987. The capacity of the balance was 3,100 g, and the resolution was 0.05 g. After modification and incorporation into the microwave drying system, the balance was calibrated with National Bureau of Standards Class S-1

calibration weights. Calibration suggested that a factor of 0.9994 should be applied to balance reading to get true weight readings. Incorporation of such a correction factor was accomplished by a simple software statement.

Computer

45. A low cost Commodore 64 computer was chosen for this study. The Commodore 64 is equipped with a BASIC interpreter stored in read-only memory (ROM), provides a user port of eight individually programmable input/output pins, and is equipped with software drivers to accommodate RS232C serial communication. A simple level shifter (TTL to RS232) is required to make the Commodore 64 completely RS232 compatible. The computer was purchased for $180 in mid-1987.

46. A microcomputer such as the Commodore 64 is ideal for controlling a process such as the one of interest for this study because it has the capability to:

a. Interface directly with the oven microprocessor through inexpensive circuitry described later.

b. Acquire weight loss data from an electronic balance by way of a standard RS232C interface.

c. Analyze data acquired to control logic flow and manipulate the oven as required through software.

47. Low cost of the computer will be of considerable advantage if it is desired to manufacture microwave drying systems for field application. The system is modular and any of the major components (computer, balance, or oven) can be easily removed and replaced. The nonintrusive interface designed for the Commodore 64 and the microwave oven allows either component to be used separately, completely independent of the other.

48. Software controlling the microwave drying process will be stored permanently in an integrated circuit chip called an EPROM (Erasable Programmable Read-Only Memory). The EPROM is housed on an inexpensive printed circuit board that plugs into the expansion bus of the Commodore 64. The printed circuit board and ROM combination operate such that when power is applied, the BASIC program in the EPROM is automatically loaded into the read-write memory of the computer and executed. No other storage device (neither a disc drive or a cassette tape recorder) is required. The cost of the EPROM and its PC board module was approximately $35 in late 1987.

Software

49. Although not strictly equipment, software controlling the process is one of the most important items in this system. A flow diagram for the process is shown in Figure 13, and software is written around this outline. Software "prompts" the user, directing in clear and unmistakable language the next step in the process. After the user has been instructed to place an empty tare on the scale and then to fill the tare with moist soil, the software takes total control of the process and needs no further assistance from the user/technician. Soil is dried by the system, an alarm sounds when the process is complete, and final water content is computed and displayed.

50. There are three distinct stages of microwave drying as shown in Figure 11 and these are somewhat reflected by three loops designated as 1, 2, and 3 in Figure 13. During the first loop, soil specimen temperature increases from ambient to a temperature where water is driven from the specimen at an approximately constant rate. As can be seen from Figure 11, the slope of the drying curve is initially flat because time is required to heat the specimen to the point where significant water loss begins. Since a prescribed small slope will be used to terminate the process, it may be inadvertently terminated during the initial stage of heating before drying effectively begins. The small slopes of stage one must be properly circumvented for drying to proceed to completion. This problem was handled by defining a quantity G which is the product of the average wet weight and the average weight change per unit time over a specified time interval. In equation form

$$G = \frac{(W_o + W_f)}{2} \times \frac{(W_o - W_f)}{\Delta t} \tag{21}$$

where

W_o = specimen weight at beginning of interval, g

W_f = specimen weight at end of interval, g

Δt = time interval, taken to be 30 sec

The quantity G rises to a peak then declines to near zero for a fully dry specimen. To get past stage one, the specimen is heated continuously as long as G increases for 30-sec intervals. When this product decreases for a 30-sec interval, experience has shown that the specimen is losing weight to

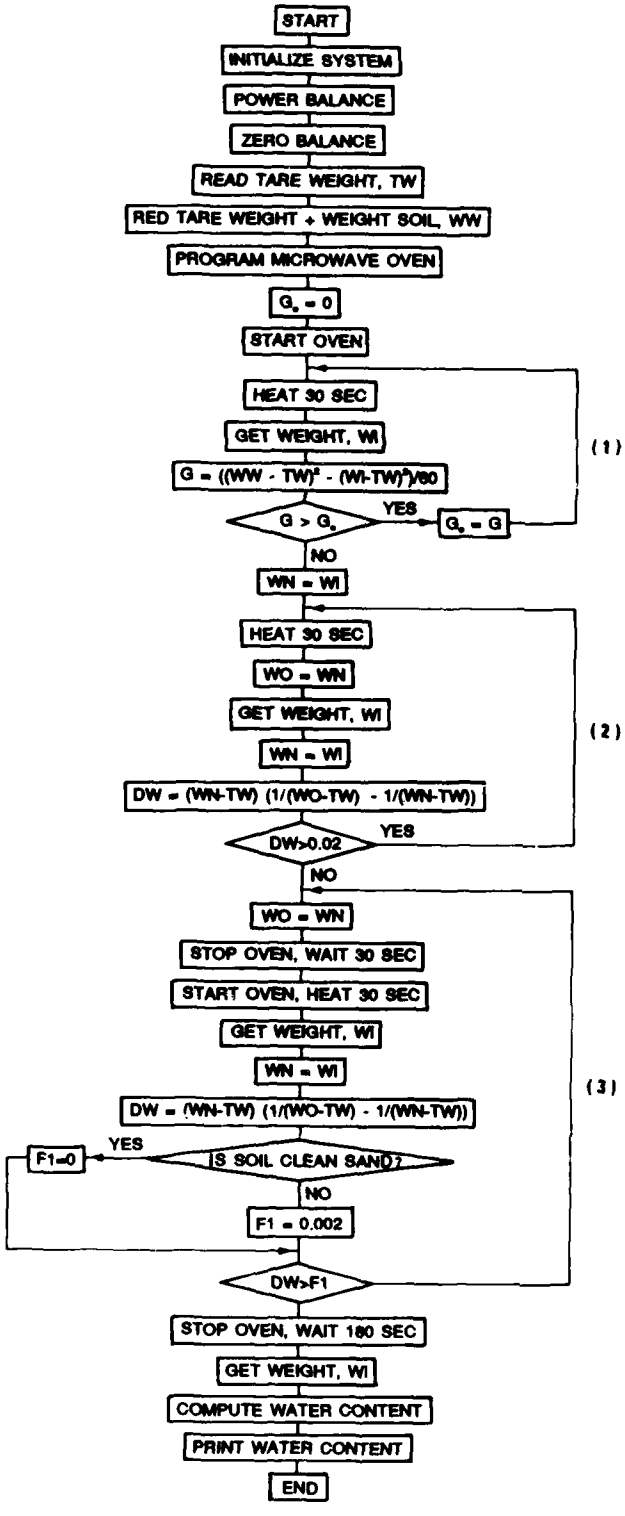

Figure 13. Flowchart of microwave drying process

the extent that the process can be considered to have safely entered the second stage.

51. During the second stage of microwave heating, microwave energy is applied continuously as long as water content changes of 2 percent or more occur during successive 30-sec intervals. If the water content change becomes less than 2 percent in a 30-sec interval, then the third stage of drying is considered to have begun and the system begins to apply half power to the specimen. That is, microwave energy is applied for 30 sec, and then the specimen is allowed to "rest" for 30 sec. The rationale for this decrease to 50-percent power is that, if there are hot spots or cold spots in the specimen, they will have time to equalize during the rest period between microwave energy applications. Error in soil water content resulting from heating to high temperature levels has been considered in the discussion of Table 3 in the section "Cohesive Soils Subjected to Microwave Drying" in Part III. Reduction to 50-percent power helps minimize such errors by reducing the cause of high temperature, which is continuous exposure to high power microwave radiation.

52. At the end of the final stage of microwave drying, water content change begins to decrease substantially with time. The terminal slope has been selected (based on experience and calibration) to be a 0.2-percent decrease in water content in 30 sec for silts and clays and a 0-percent water content change in 30 sec for clean sands.

53. When the terminal slope is reached, the process is terminated, the specimen is allowed to set in the oven for 3 min to allow any water vapor condensation on the container to vaporize, an alarm sounds, water content is computed and displayed, and the test is declared to be over.

54. A complete software listing is shown in Appendix A.

Empty Oven Load

55. As was stated earlier, the magnetron tube of a microwave oven will suffer severe damage if allowed to radiate into an empty oven for extended periods. As more and more water is removed from a soil specimen, there will come a point when the oven is, for all practical purposes, operating empty and damage may occur if further steps are not taken to prevent energy feedback to the magnetron. An "empty oven" load must be provided to absorb microwave

energy when (essentially) all water has left the specimen.

56. Two ordinary unglazed fire bricks were determined by trial and error to be an effective and sufficient empty oven load and were placed permanently in the oven. These bricks heat up during microwave drying of soil specimens and obviously absorb some oven power (and slow the soil drying process). However, this power sacrifice must be tolerated to ensure that the oven is protected under conditions of low load which is a necessary part of the soil drying process.

Supplementary Electronics

57. Communication between the Commodore 64 computer and the microwave oven controlling computer is necessary to fully automate microwave drying. To achieve the automation required for this investigation, special and unique circuitry was required to enable the computers to communicate in order to allow the Commodore 64 to indirectly manipulate the microwave oven. External devices (such as printers, modems, and other computers) may communicate with the Commodore 64 computer used in this study through the user port. The user port is accessed via a 24-pin male edge connector, which connects directly to one of the internal 6526 CIA chips of the Commodore 64 (Commodore Business Machines, Inc. 1983). The microwave oven used in this study contains an onboard microcomputer which may be programmed for ordinary cooking purposes through a membrane keyboard on the oven's front panel. Microwave oven drying of soil requires a process which involves measuring the time rate of weight loss of the soil specimen during drying. Therefore, the oven microcomputer alone is not sufficient for soil drying, since weight loss data must be acquired and analyzed so that decisions may be made to systematically control the process.

58. The oven microcomputer is normally controlled through the membrane keyboard which initiates various operating times and programs by contact closures. These contact closures are recognized by the oven microcomputer which executes certain software in response. For example (Figure 14), if the "CLEAR" key on the membrane keyboard is pressed, a path is made from C5 to A2 and, in response, the oven microcomputer clears itself as well as its display and then sounds a tone.

59. The microwave oven microcomputer responds predictably when given a

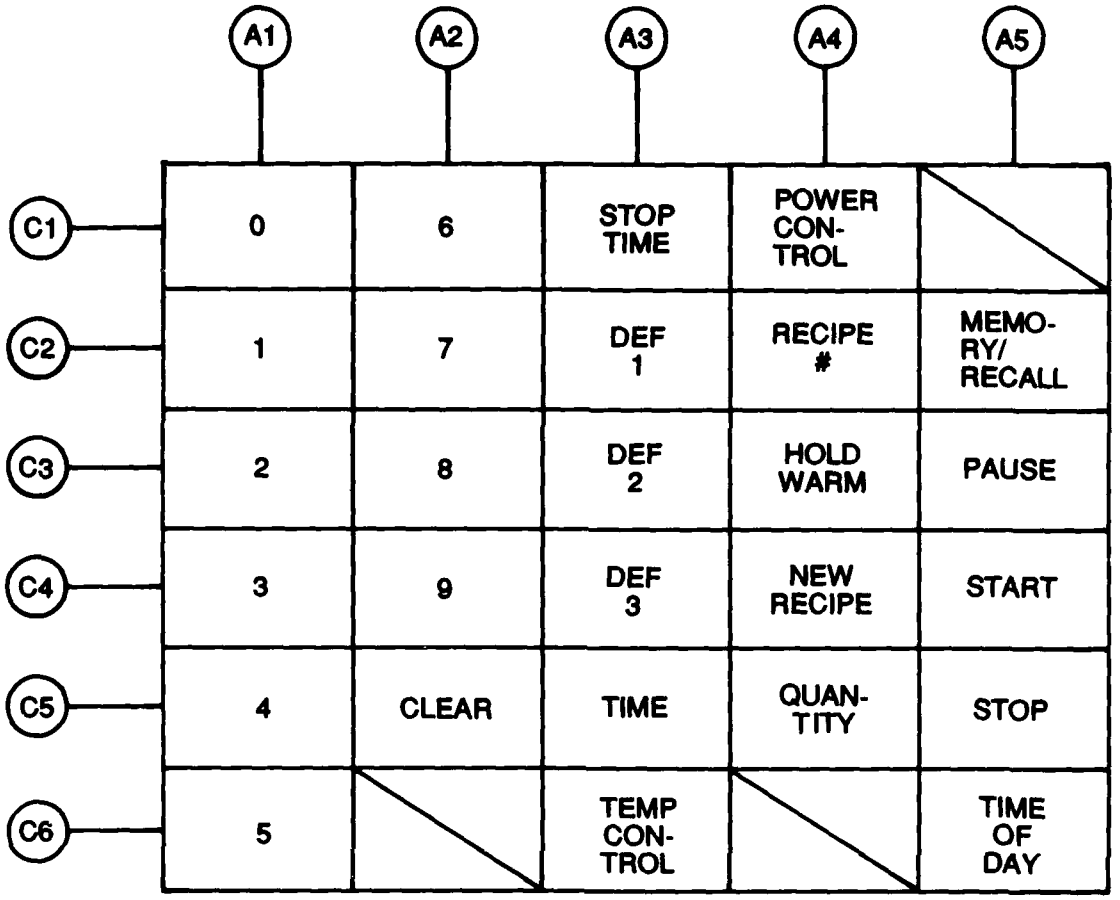

Figure 14. Microwave oven keypad panel matrix

sequence of keystrokes. In considering this fact, it was recognized that an interface to the microwave oven and all its resources could be made through the keyboard. It was determined that access to six of the functions of the microwave oven would be sufficient to perform automatic drying (Table 4), and an interface system was designed around this requirement. It should be noted that the interface system design leaves all the normal safety features built into the oven intact, eliminates the need to modify the power circuits of the oven, and allows complete control of the oven through a relatively simple circuit.

60. The computer to oven keyboard circuit is shown in Figure 15 and is made of integrated circuit (IC) chips costing less than $10 per chip. The AD7511D1 devices shown in Figure 15 are semiconductor switches made by Analog Devices of Norwood, MA. These electronically activated switches are single-pole, single-throw with each IC chip containing four switches. Two of the

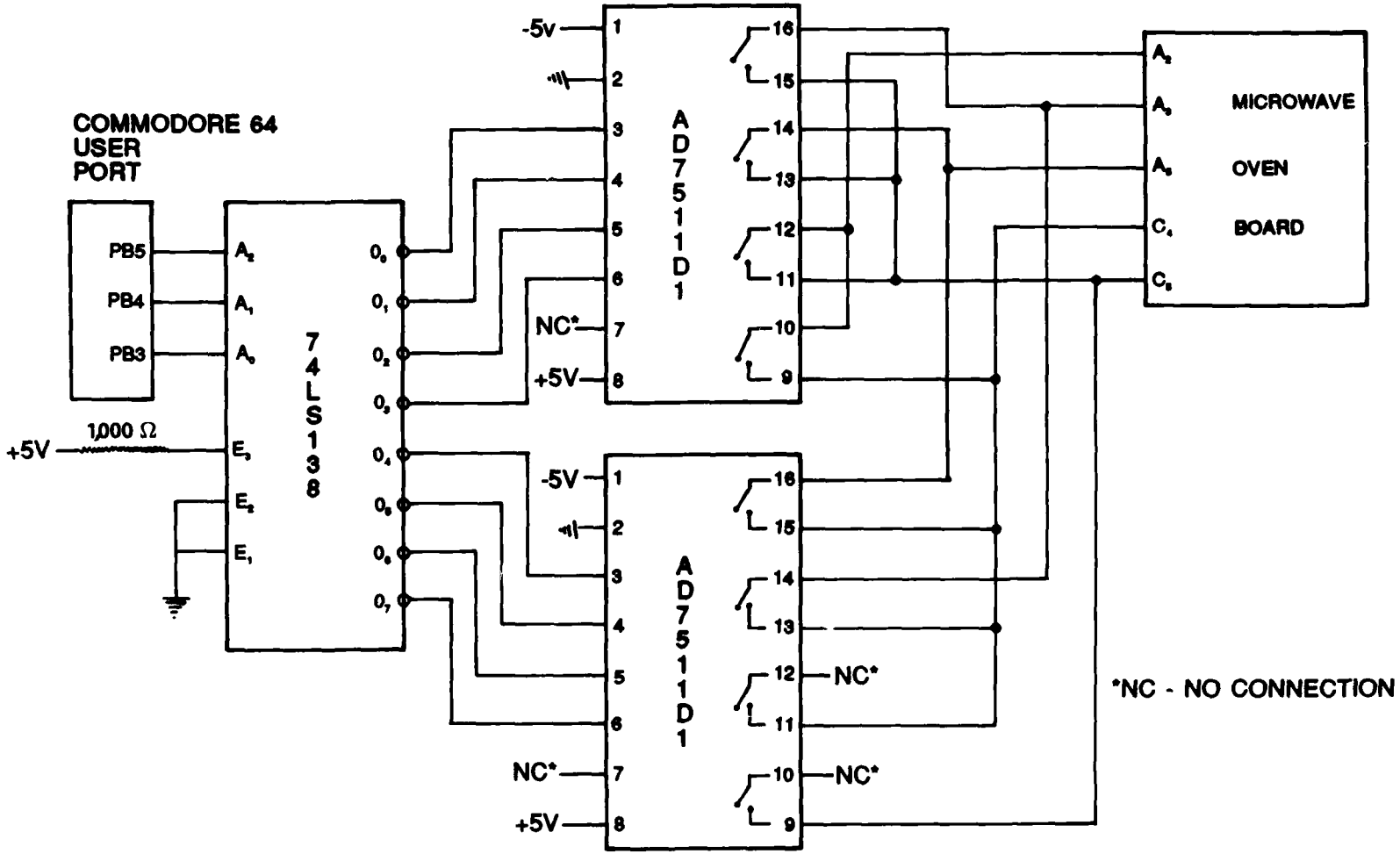

Figure 15. Commodore 64 to microwave oven board interface circuit

AD7511D1 semiconductor switch packages were required to provide the functions necessary for automatic drying. The 74LS138 device is a 3 to 8 line decoder that allows the Commodore 64 to use three binary output lines to control the eight electronic switches, not all of which are used in this application.

61. Commands are sent to the semiconductor switches by way of the 74LS138 decoder from the user port of the Commodore 64 microcomputer, which allows control of Port B on the CIA 6526 chip No. 1 (Commodore Business Machines, Inc. 1983). Port B provides 8 lines which can be programmed as inputs or outputs by the Port B data direction register (DDRB). Data register B (DRB) is Port B where data is actually written. The definition of Port B as input or output is specified on a pin-by-pin basis by the data written to DDRB. The port can be accessed by the BASIC commands "Peek" (read) and "Poke" (write). The address of DDRB is 56579 while the address of DRB is 56577. These addresses are uniquely defined for the Commodore 64. Port B bits 5, 4, and 3 are defined as outputs while bits 0, 1, 2, 6, and 7 are defined as inputs by poking 56 to DDRB. Table 4 shows the bit values written to DRB by poking the value in the data column to DRB. The right-most column indicates the function activated on the oven keyboard. As shown in Figure 15, the A_2, A_1, A_0 inputs to the 74LS138 are connected to bits 5, 4, and 3 of Port B, respectively. Notice that the bit number in the Port B data register is the same number that equals 2 raised to the power to turn that bit (or bits) on. For example, to CLEAR, poke the number 16 which is

$$00010000 = 0 \times 2^7 + 0 \times 2^6 + 0 \times 2^5 + 1 \times 2^4 + 0 \times 2^3 + 0 \times 2^2 + 0 \times 2^1 + 0 \times 2^0 = 16$$

To activate 9 on the keyboard, poke 24 which is

$$00011000 = 1 \times 2^4 + 1 \times 2^3 = 24$$

Table 5 shows a complete truth table for the 74LS138 to microwave function.

62. IC chips used in the special control circuitry were excited with ±5 v DC. Plus 5 v is available from the computer and minus 5 v is available from the circuitry of the microwave oven. These levels are somewhat lower than those recommended for optimum performance of the semiconductor switch

chips. For example, time response of these chips is of the order of nanoseconds when they are excited by manufacturer recommended voltage. However, nanosecond response time is not required for this application, and experience has shown that all chips used perform perfectly well at the excitation level provided.

Microwave Oven System

63. Individual components of the microwave system and their function have been described above. Perhaps the most significant arrangement of mechanical components in the system is that between the oven and the balance. A descriptive cutaway section of the oven-balance system is shown in Figure 16. The oven used in this study is of double bottom liner construction. As can be seen in the figure, the outer liner of the oven is cut away to allow the casing of the balance to contact the inner liner so as to minimize the load button length. The load button, which is about 3/8 in. diam, is constructed of Teflon with a conical head and extends into the oven just far enough to allow about 0.1-in. clearance between the Teflon platform (which sets on the conical head of the load button) and the inner oven liner. The hole in the inner liner through which the load button extends is about 0.050 in. larger than 3/8 in. Microwave leakage through this hole is minimal because the wavelength of radiation inside the oven is about 12.24 cm which is more than 10 times larger than the hole. Therefore, no leakage should occur. Nevertheless, leakage was checked with a microwave leakage detector and found to be virtually undetectable.

64. The oven and balance were fastened together on a simple frame consisting of two 1/4-in. aluminum plates with the oven mounted on the top plate, the balance mounted on the bottom plate, and the plates held in the correct relative position with spacer sleeves or blocks securely bolted together. Three leveling screws were threaded into the bottom plate to allow the system to be leveled for proper operation of the balance. Also shown in the figure is a single screw which fastens the inner oven liner securely to the casing of the balance and prevents buckling of the liner because if this liner buckles during a test due to thermal stress, it is likely that upward thrust of the liner would lift the Teflon platform, interfere with weighing the specimen on the platform, and ruin the test.

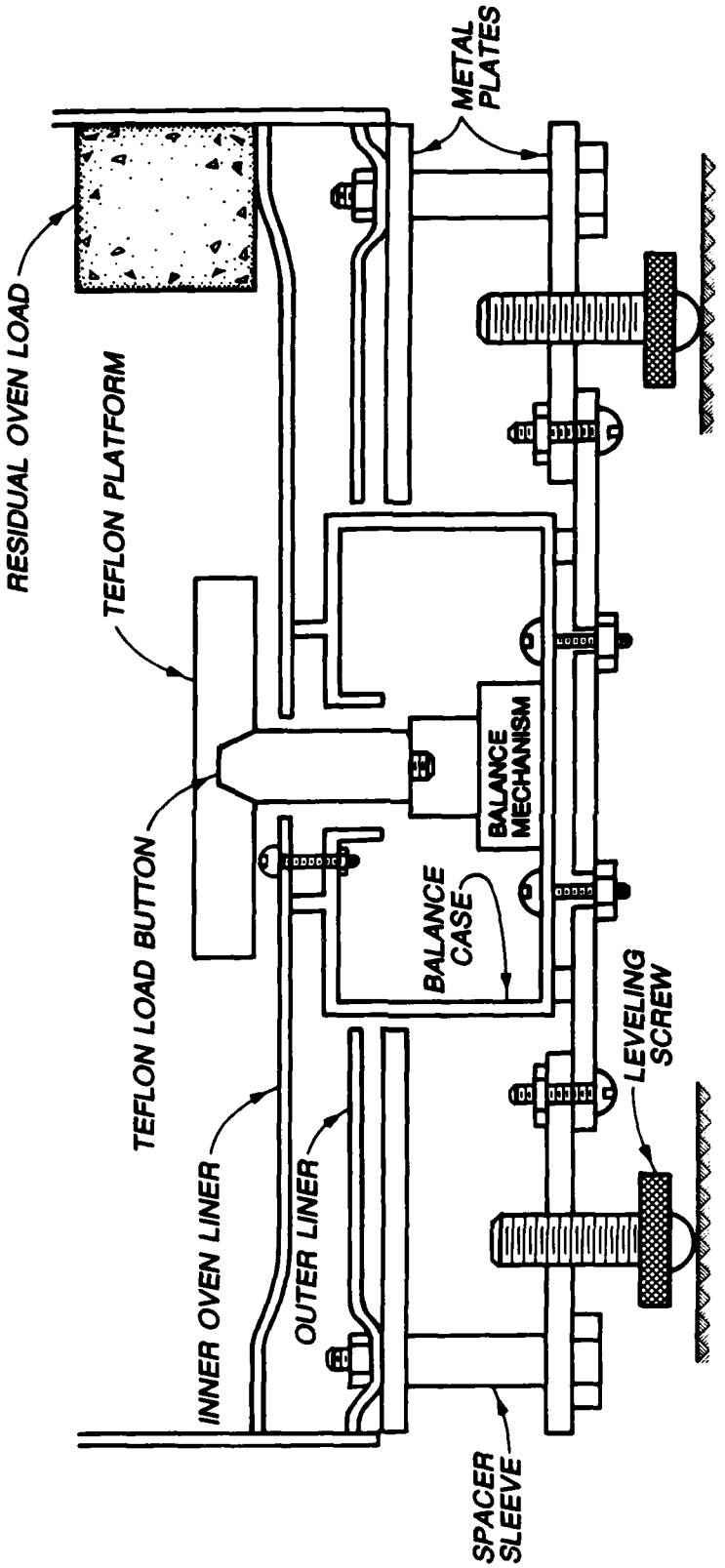

Figure 16. Section of oven-balance system

65. All components of the microwave oven system are shown in Figure 17. These components consist of the microwave oven, balance, and mounting frame as well as the computer, monitor, and printer. A hard copy of the microwave drying data is available with the printer whose use must be specified in initialization of the system.

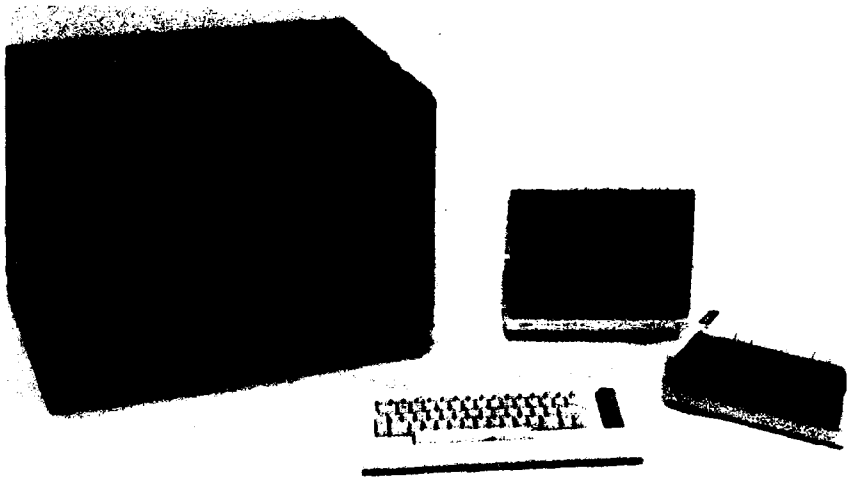

Figure 17. Components of the microwave drying system

Conventional Oven

66. The constant temperature oven used in this investigation was a BLUE M STABIL-THERM oven manufactured by the Blue M Electric Company of Blue Island, IL. The oven temperature range is 38° to 260° C (100° to 500° F) and the output power rating is 2,400 w. Oven temperature, which is thermostatically controlled, was set at 110° ± 5° C (230° ± 9° F) and was continuously monitored during this investigation at the top of the oven with a mercury thermometer.

Specimen Containers

67. Pyrex borosilicate glass beakers (250, 400, and 600 mℓ) were used in this investigation for water content specimen containers in tests performed in the microwave oven as well as in the conventional oven. These containers heat up slightly when subjected to microwave radiation but are otherwise

unreactive. Large, tall containers should not be used in the microwave oven because hot water vapor rising from a soil specimen in the bottom of a deep, tall container will condense on the cool vessel walls at the top and not revaporize easily. Specimen containers should be filled about two thirds full to minimize this potential problem.

68. A special closed container was required for drying intact soils which explode from internal vapor pressure produced by microwave heating. The container consisted of a glass jar with a polyethylene screw-on cap in which several holes had been drilled. Polyethylene plastic is unreactive to microwave radiation and the holes allowed escape of water vapor, preventing pressure buildup and possible container explosion. Such containers are available from chemistry supply and container vendors at a very modest cost. For example, the closed containers used in this investigation were obtained from Texberry Container Corporation of Houston, TX. In mid-1987 the cost of a 32-oz container (jar and lid) was less than $0.60, and the cost of a 16-oz container was less than $0.50.

69. Styrofoam containers with Styrofoam lids were used for oven power calibration tests. Styrofoam is an ideal material for such a test because it will transmit microwaves, but is an excellent insulator because it will retain heat.

70. Untempered glass of any kind should not be placed in a microwave oven because it will shatter from thermal stress.

PART V: EXPERIMENTAL PROCEDURE AND PRESENTATION OF RESULTS

Materials Tested

71. Several materials were tested in this study to demonstrate that the drying system works effectively on a variety of soil types. A number of clays, silts, and sands were tested in the program. The materials classified as clay are Vicksburg buckshot, aquagel, San Francisco Bay mud, a clay from the Atchafalaya River Basin in Louisiana, and two organic clays from Wilmington Harbor in North Carolina. Materials classified as silts tested in the program are Boston blue clay, Vicksburg loess, Georgia kaolin, and a silty clay from Enid Dam in Mississippi. Sands were LSI-30 sand and banding sand. Additionally, a crushed limestone ballast material was tested.

72. The materials tested are listed on Table 6 which also includes the Atterberg limits and a brief description of each soil. Additionally, for reference the cohesive soils tested in the program are (except for aquagel) plotted on the plasticity chart of the Unified Soil Classification System (USCS) as seen in Figure 18.

Specimen Preparation

73. Undisturbed as well as remolded specimens were tested in this investigation. Undisturbed materials were Boston blue clay, San Francisco Bay mud, a plastic clay from the Atchafalaya River Basin in Louisiana, a compacted soil from the embankment of Enid Dam in Mississippi, and two organic soils from Wilmington, NC. The other materials were remolded clays or cohesionless granular soils.

74. In all cases test specimens and controls were prepared in a humid room maintained at approximately 95-percent relative humidity. An amount of soil which would be split into control and test specimens was placed on a glass plate and mixed thoroughly in an effort to ensure that the same water content would be obtained for the control and the test. That material was then "split" into two beakers for drying, the control portion was dried in the conventional oven, and the test portion was dried in the microwave oven.

75. Dry remolded soils were wetted up to the desired water content and forced through a US Standard Sieve No. 4 (4.75 mm) and then allowed to cure in

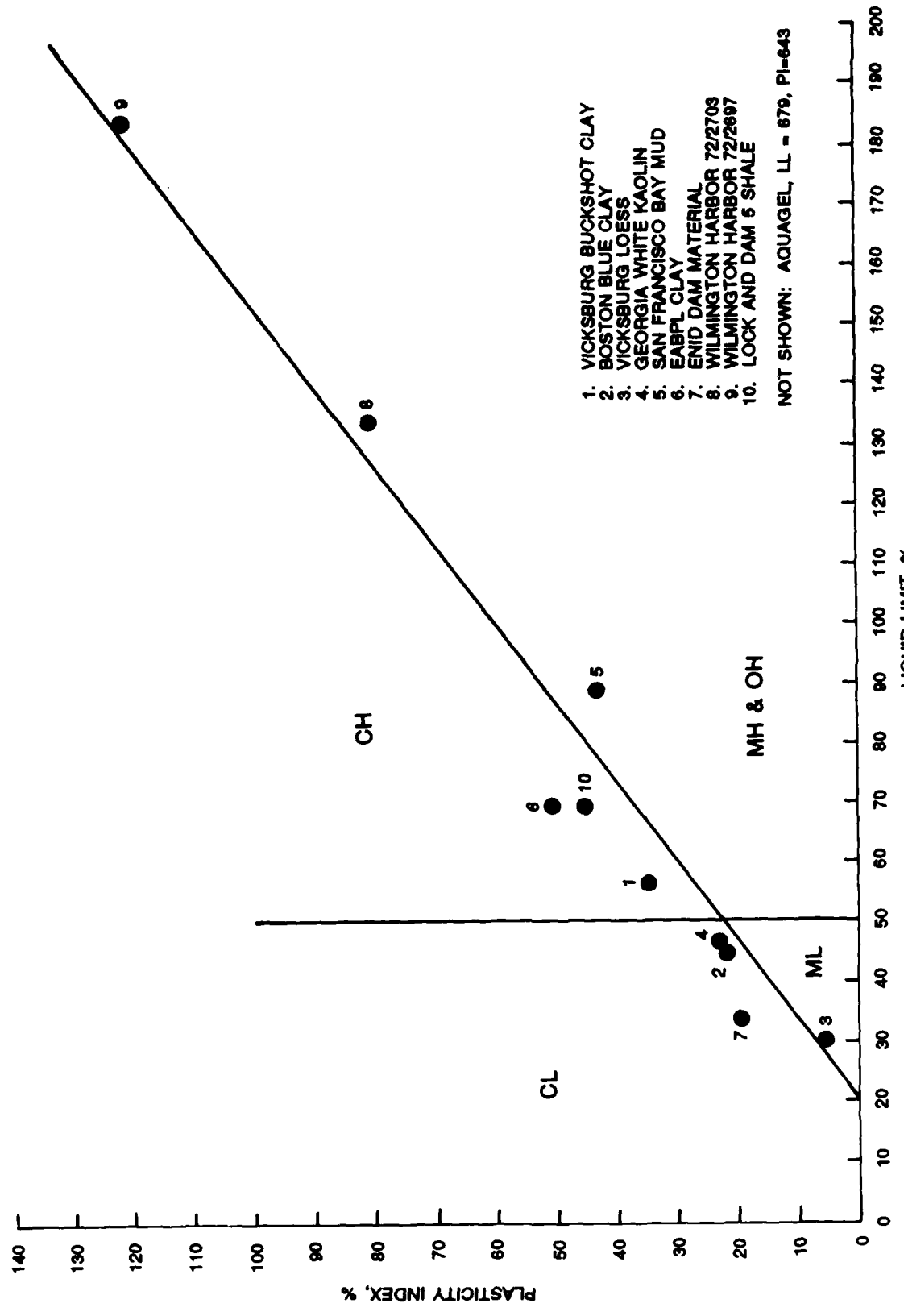

Figure 18. USCS plasticity chart with data points for cohesive materials used in testing program

closed containers for a minimum of 3 days before use.

Presentation of Results

76. A program of study was conducted on materials of this investigation in which water content determined from the conventional oven (control tests) was compared with water content determined using the microwave oven system. Specimens were considered dry in the microwave oven when water content decrease during a 30-sec interval of microwave exposure was less than or equal to 0.2 percent for materials containing plastic fines, and 0.0 percent for clean granular materials. A variety of materials was studied in this investigation to demonstrate that the system works effectively on a broad spectrum of soils.

77. Studies were conducted to investigate the effect of specimen mass, particle size, and, to a lesser extent, water content.

78. All tests conducted in the investigation are summarized in Table 7 which compiles microwave and conventional oven water contents showing differences between the two values and the percent difference along with the initial specimen mass and time required for microwave drying. Additionally, time versus water content data are presented in the tables of Appendix B for all tests performed. Examination of Table 7 shows a favorable comparison between microwave oven and conventional oven water contents. In more cases than not the conventional oven water content was slightly larger than the microwave-oven-determined values but the differences are small, especially for materials with lower water contents. Differences tend to be higher with soils of high water content and high plasticity such as aquagel and the Wilmington Harbor 72/7203 material, but the percent difference for these materials was small. The overall comparison between the microwave and conventional oven water contents is considered to be very favorable, and the test procedure and equipment are successful.

79. One possible departure from standard accepted procedure should be pointed out; a material containing as much volatile organic material as Wilmington Harbor 72/7203 should possibly be dried in a 60° C constant temperature oven. However, a 110° ± 5° C oven was used. The conventional oven water content was 4.9 percent higher for the material and would have been lower (and possibly closer to the microwave oven water content) if a 60° C

oven had been used. However, this test is shown to demonstrate that highly organic materials may be dried with this system without the danger of fire.

Effect of Soil Particle Size

80. As was discussed earlier, power is lost to each successive layer of material in a body being heated by microwaves; therefore, less power is available in the interior of a continuous body than at the surface. If power does not reach the interior of a body of soil with sufficient density to ensure heating (and hence drying) there, then there is danger that the interior of a soil specimen will not dry to the same extent as the surface, causing the overall water content of the soil specimen to be in error. There is also a question as to whether or not water vapor can escape from a material being heated quickly enough to ensure predictable drying. To investigate these uncertainties, samples of compacted Vicksburg buckshot clay were tested in the microwave and the conventional oven. Soil specimens 4 in. diam by 4.75 in. high were compacted with standard effort at a water content (about 22 percent) known to be optimum for this effort. Two specimens 4 in. diam and 3 in. high were dried in the microwave oven. Another specimen was broken up into approximately 1.5-in.-diam "chunks" and dried. A third specimen consisting only of uncompacted 0.1-in. granules was dried in the oven. All these soil specimens were of about equal mass (1,190 g on average) and required about 1,690 sec to dry.

81. The results of these tests are summarized in Table 8. The tests are also shown in Table 7 opposite Vicksburg buckshot clay. There is no statistically significant or systematic difference in either water content determined or time required in the microwave oven for this remolded and compacted soil. Therefore, the conclusion must be that in a cylinder up to 4 in. in diameter and 4 in. long of compacted soil dried in an oven delivering 700 w of output power, particle size is no deterrent to drying.

82. However, specimens of intact Boston blue clay dried in the microwave oven had to be contained in a closed capped jar (with holes drilled in the cap, described in the section "Specimen Containers" in Part IV) because water vaporizing inside the brittle soil produced an explosion which blew material out of topless tares, ruining these tests. Cylinders of intact Boston blue clay (2 in. diam and about 3 in. high) were placed in the oven.

During microwave drying, these cylinders were completely "rubbelized" by water vapor pressure explosion. A comparison of posttest specimens of undisturbed Boston blue clay is shown in Figure 19. It is seen in the figure that the conventional oven specimen retained its cylindrical form and showed little macroscopic structural damage as a result of drying, whereas the microwave oven specimen (which was initially identical in appearance to the conventional oven specimen) was reduced to a pile of flakes by the drying process.

Figure 19. Posttest comparison of undisturbed Boston blue clay

83. Water vaporizing rapidly inside soft remolded clays as the result of microwave drying left the imprint of vapor bubbles in the soil to give the dry specimen a "honeycomb" texture. This can be seen quite dramatically in Figure 20. However, an identical specimen of the same clay produced no such texture when dried in the conventional oven. The texture of the conventional-oven-dried specimen is smooth as can be seen in Figure 21. The explanation is that water is vaporized slowly enough in conventional oven drying that it does not alter the structure of the soil as it escapes. However, there was no indication that water vapor could not escape rapidly enough from soil in any test performed in this investigation. It should be mentioned that in the drying of hard brittle rock and gravel particles (which was beyond the scope of this study), extremely high vapor pressure could develop within a particle, producing an explosion which could prove extremely dangerous. Adequate containment must be provided in the drying of such materials to avoid hazards to

Figure 20. Honeycomb texture of microwave-dried remolded clay specimen

Figure 21. Smooth texture of conventional-oven-dried remolded clay specimen

equipment and personnel, and containment might consist of an outer vessel made of polyethylene or Styrofoam. These materials are transparent to microwaves and therefore would not diminish power transmitted to the specimen, yet would contain an explosion and prevent damage to the equipment. The outer "containment" vessel would be part of the tare weight and should be handled as such. However, provision must be made in such vessels to allow for the escape of water vapor.

Effect of Specimen Mass

84. Gilbert (1974) and Charlie, Von Guten, and Doehrmy (1982) performed microwave oven power calibrations with water and showed that power absorbed by a (pure water) specimen varied directly with the mass of the specimen. A power calibration was performed for the present study and confirms the general findings of the earlier studies. Equation 16 suggests proportionality between power absorbed by (and consequently heat generated within) a specimen and the volume (mass) of the specimen, all other factors being equal. A further implication of the microwave oven power/load relationship (as contained in Equation 16 and confirmed with a power calibration) is that there may be an optimum soil specimen size for most efficient microwave drying. Too small a specimen utilizes oven power inefficiently and too large a specimen requires a long time exposure and the expenditure of a large amount of energy. These hypotheses are confirmed by considering the entries of Table 9 which clearly show relatively long drying periods for small specimens and extended periods of time required for larger specimens. For example, a 20-g specimen of San Francisco Bay mud required 341 sec to dry, whereas 160-g specimens required (an average of) 805 sec, indicating that a specimen with 8 times the mass of an otherwise identical specimen required less than 2-1/2 times the time to dry. A similar trend showing inefficiency in the drying of small specimens and the trend for long drying times in larger specimens is unmistakably seen in the other two soil entries in the table.

85. Two other observations from the table which are believed to be significant are (a) differences in water content between control and microwave oven tests decrease as specimen size increases, and (b) differences between controls and tests decrease with decreasing plasticity index, aquagel being the most plastic and Vicksburg silty clay being the least plastic material in the table.

86. Experience gained from this investigation suggests that specimens with an initial mass from 80 to 200 g are adequate and yield microwave oven water contents which compare favorably with those determined in the constant temperature oven. Additionally, specimens in this size range do not require extended drying periods. This fact should prove advantageous for energy conservation and test productivity.

Microwave Oven Procedures by Others

87. The advantages of using microwave ovens to dry soils have been recognized since the introduction of microwave ovens in the 1950's. However, problems in using these devices for drying soil are also well recognized. Serious research to address and resolve problems associated with microwave drying has been ongoing since the mid-1960's. All of the problems were never adequately resolved, but in the meantime, microwave oven use for soil water content determination began to increase substantially. Recognizing that microwave oven use was on the increase, the ASTM and the US Department of the Interior, Bureau of Reclamation (USBR) prepared a standard procedure for determining soil water content using a microwave oven.

88. The ASTM and USBR procedures (ASTM 1988, USBR 1986) are essentially identical as far as oven use is concerned and involve:

a. Heating the specimen initially for 3 min continuously then removing the test specimen and mixing the soil with a spatula or knife.

b. Heating the specimen subsequently in 1-min increments then removing, weighing, and mixing the soil until the weight decrease over a 1-min time interval is less than 0.1 percent of the initial wet weight.

89. These procedures are not entirely objectionable and under some conditions with some materials could yield good results. Problems may arise from the procedures since specimens must be repeatedly removed from the oven and serviced by (generally many) operators. Potential problems may be that:

a. Soil is lost during the mixing of a sample causing an erroneous water content.

b. A hot container may be dropped.

c. Each operator will take a different amount of time to weigh and mix the soil. The amount of cooling time may affect the ultimate water content of some materials. Therefore, the

results from these procedures may not be entirely operator independent.

d. Many weighings, calculations, and recordings in rapid time succession substantially increase the possibility of operator blunder.

90. The microwave drying system developed during this research suffers from none of these problems. Once in place, the soil is not touched again. All weighing takes place inside the oven, untouched by the operator, and all calculations and decisions are made (consistently) by a microcomputer. Water contents, including the final water content, are calculated and printed for the operator.

PART VI: CONCLUSIONS AND RECOMMENDATIONS

91. In this investigation, equipment was developed and described for drying soil which produced a high correlation with water contents determined in the conventional, constant temperature oven. The equipment is a microwave oven under computer and software control in which a soil specimen is weighed continuously during drying, and the computer acquires and evaluates weight change data to control the drying process. In this manner water contents are produced in the microwave oven equivalent to those determined in the conventional, constant temperature oven in typically one-hundredth the time.

92. The system was demonstrated to dry "normal" soils, that is, those of which an embankment would usually be constructed as well as some moderately organic soils and some pure clay minerals. The system determines the weight of the soil container in use before each test and prompts the user, requiring only that the user fill the tare with moist soil and close the door of the oven. One additional input required by the system is whether or not the material under test is a clean sand. The user must determine this by inspection, but such a determination is not believed to pose a severe problem.

93. Based on tests conducted in this investigation and comparison of results with the work of other investigations, the following conclusions are believed warranted:

a. An automated microwave oven drying system has been developed and described in this investigation which allows safe and reliable drying of soil specimen for water content determination.

b. Specimens used with the equipment described should have an initial mass between 80 and 200 g. Smaller specimens will not dry as efficiently and will likely yield a less accurate water content, especially for highly plastic soils. Larger specimens will result in a longer time required for drying and unnecessary energy expenditure.

c. Water content determination in the microwave oven appears to be unaffected by particle size, that is the size of a chunk or clump of clay. However, if it is convenient and will not otherwise affect test results, it is recommended that larger chunks of clay be broken down into 1-in. (or less) particles.

d. Containers used in the microwave oven should be able to transmit microwaves and this excludes metal containers. Tempered borosilicate glass beakers are recommended.

e. Some undisturbed low permeability soils will explode upon exposure to microwave heating. Such soils must be contained in capped vessels with adequate provision made to allow escape of

water vapor. Rock and gravel fragments subject to microwave heating may explode with such force and intensity as to constitute a safety threat. If such materials are used in a microwave oven, then adequate containment must be provided to avoid equipment damage and personal injury. Adequate containment may consist of an outer tare vessel made of polyethylene or Styrofoam which would transmit microwave energy, yet contain an exploding gravel particle.

f. Untempered glass should not be placed in a microwave oven.

g. A microwave oven should not be used to dry soil without the provision of an "empty oven load." Otherwise, the magnetron may be severely damaged.

h. A specimen container should not be used in which there is only a small amount of soil. The soil specimen should always fill at least two-thirds of the container; otherwise, water vapor will condense on the cool upper walls of the container.

94. Even though the microwave drying equipment developed in this study has been reasonably well demonstrated to work safely and effectively on a variety of materials, it is recommended that when each new material is dried for the first time, material response and equipment be monitored closely and that results be confirmed in a constant temperature oven--the reason being that a new untested material may contain minerals which produce an unexpected reaction upon microwave heating (such as explosions or oxidation) or minerals which dehydrate undesirably to yield erroneous water content information. This equipment like all other laboratory equipment should be used with judgment and common sense. If, during use, an unexpected or seemingly dangerous phenomenon is observed, then use should be discontinued until the phenomenon can be explained and/or determined to be safe.

95. Soils with no unusual properties were studied and tested in this investigation. However, other significant soil types must be utilized and dealt with in civil construction and military operations making it sometimes necessary to rapidly determine the water content of materials such as highly organic soils, soils containing peat, soils containing gypsum, dredged material with very high water content, and large particle soils such as gravels and earth-rock fills.

96. The automated microwave system as described herein is a very valuable instrument with many potential uses. Its value to soil mechanics may be increased even further if it can handle the soil types named above. For example, its use may be extended into the military areas for uses such as the selection of materials for the construction of expedient structures or for the

evaluation of terrain for military vehicle mobility.

97. Therefore, it is recommended that additional research be performed on the automated microwave system to extend its use to many more soils.

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Table 1

Magnetic Permeabilities (after Kraus and Carver 1973)

Substance	Group Type	Relative Permeability μ_r
Bismuth	Diamagnetic	0.99983
Silver		0.99998
Lead		0.999983
Copper		0.999991
Water		0.999991
Vacuum	Nonmagnetic	1 (by definition)
Air	Paramagnetic	1.0000004
Aluminum	Paramagnetic	1.00002
Palladium	Paramagnetic	1.0008
2-81 Permalloy powder (2 Mo, 81 Ni)*	Ferromagnetic	130.0
Cobalt		250.0
Nickel		600.0
Ferroxcube 3 (Mn-Zn-ferrite)		1,500.0
Mild steel (0.2 C)		2,000.0
Iron (0.2 impurity)		5,000.0
Silicon iron** (4 Si)		7,000.0
78 Permalloy (78.5 Ni)		100,000.0
Purified iron (0.05 impurity)		200,000.0
Supermalloy (5 Mo, 79 Ni)		1,000,000.0

* Percentage composition. Remainder is iron and impurities.
** Used in power transformers.

Table 2

Relative Dielectric Constants (after Kraus and Carver 1973)

Medium	Constants
Vacuum	1.0 (by definition)
Air (atmospheric pressure)	1.0006
Paraffin	2.1
Polystyrene	2.7
Amber	3.0
Rubber	3.0
Sulfur	4.0
Quartz	5.0
Bakelite	5.0
Lead glass	6.0
Mica	6.0
Marble	8.0
Flint glass	10.0
Ammonia (liquid)	22.0
Glycerin	50.0
Water (distilled)	81.0
Rutile (TiO_2)	114.0
Barium titantate ($BaTiO_3$)	1,200 at 25° C
Barium strontium titanate (2 $BaTiO_3$: 1 $SrTiO_3$)	10,000 at 25° C

Table 3

Change in Water Content from 100° to 200° C for Clay Minerals

(after Grim 1968)

Clay Mineral	Change in Water Content from 100° to 150° C %	Change in Water Content from 100° to 200° C %
Illite		
Gilead, Calhoun Co., IL	0.40	0.85
Fithian, Vermilion Co., IL	0.29	0.58
	0.32	0.56
Muscovite		
Coarse	0.22	0.27
Finely ground	0.56	0.96
	0.48	0.91
Hectorite		
Hector, CA	0.36	0.72
Montmorillonite		
Belle Fourche, SD	0.16	0.24
Tatatilla, Mexico	3.61	4.83
Montmorillon, France	1.89	2.78
Pontotoc, MS	1.08	1.62
Nontronite		
Sandy Ridge, SC	0.75	1.08
Spokane, WA	1.83	2.59
Kaolinite		
Ione, CA	0.00	0.00
	0.05	0.11
Biotite	0.49	1.02
Phlogopite	0.27	0.61
Halloysite		
Liége, Belgium	1.15	1.60
	0.39	0.66
Adams Co., OH	0.47	0.56
Hickory, NC	0.17	0.68
Allophane		
Moorefield, KY	2.06	4.17
Anauxite		
Mokelumne River, CA	0.28	0.38
Penninite		
Paradise Range, NV	0.06	0.11
Chlorite		
Danville, VA	0.09	0.19

(Continued)

Table 3 (Concluded)

Clay Mineral	Change in Water Content from 100° to 150° C %	Change in Water Content from 100° to 200° C %
Palygorskite (Mountain Leather), MT	0.75	3.18
Sericite Prince Rupert, BC	0.00	0.00
Vermiculite North Carolina	0.96	1.34
Glauconite Lyons Wharf, MD	0.53	0.79
Sepiolite Asia Minor	0.84	1.76

Table 4

Port B Data Register Through the User Port to Microwave Oven

Bit No.									
7	6	5	4	3	2	1	0	Data	Function
0	0	0	0	0	0	0	0	0	TIME
0	0	0	0	1	0	0	0	8	STOP
0	0	0	1	0	0	0	0	16	CLEAR
0	0	0	1	1	0	0	0	24	NINE
0	0	1	0	0	0	0	0	32	START
0	0	1	0	1	0	0	0	40	UNUSED
0	0	1	1	0	0	0	0	48	UNUSED
0	0	1	1	1	0	0	0	56	RESET
		A_2	A_1	A_0					

Table 5

Function Table for 74LS138 Decoder

Inputs						Outputs								
E_1	E_2	E_3	A_2	A_1	A_0	$\overline{0}$	$\overline{1}$	$\overline{2}$	$\overline{3}$	$\overline{4}$	$\overline{5}$	$\overline{6}$	$\overline{7}$	Function
0	0	1	0	0	0	0	1	1	1	1	1	1	1	TIME
0	0	1	0	0	1	1	0	1	1	1	1	1	1	STOP
0	0	1	0	1	0	1	1	0	1	1	1	1	1	CLEAR
0	0	1	0	1	1	1	1	1	0	1	1	1	1	NINE
0	0	1	1	0	0	1	1	1	1	0	1	1	1	START
0	0	1	1	0	1	1	1	1	1	1	0	1	1	--
0	0	1	1	1	0	1	1	1	1	1	1	0	1	--
0	0	1	1	1	1	1	1	1	1	1	1	1	0	RESET

Note: 1 = High voltage level.
0 = Low voltage level.

Table 6

Description of Materials Tested

Material	Atterberg Limit, % LL	PL	PI	Description
Vicksburg buckshot clay (CH)	56	22	34	Dark-brown, plastic, inorganic clay. An alluvial soil composed of silt- and clay-size particles of montmorillonite with some quartz and illite. This material is extremely sticky and plastic when wet
Boston blue clay (CL)	44	22	22	Blue-gray, glacial, marine, silty clay underlying the greater Boston area, consisting of clay- and silt-size particles with some fine sand. The predominant mineral is illite with a small amount of montmorillonite
Vicksburg loess (ML)	29	23	6	Fine-grained, loessial soil found around Vicksburg, MS, 99 percent of the material passes the No. 200 sieve and the predominant mineral is montmorillonite
Vicksburg loess and sand	--	--	--	A mixture of 41-percent Vicksburg loess and 59-percent concrete sand. The concrete sand is a washed, medium coarse quartz sand from Hattisburg, MS
Aquagel (CH)	679	36	643	Commercial-bentonite drilling mud, approximately 95-percent montmorillonite
Georgia kaolin (CL)	46	23	23	Commercial grade of white kaolin clay from Georgia, consists of about 97-percent kaolinite
San Francisco Bay mud (OH)	88	43	45	Fine-grained, slightly organic (1-2 percent total carbon), dark-gray, plastic, marine clay from the San Francisco Bay area consisting predominantly of montmorillonite
EABPL* clay (CH)	69	19	50	Dark-gray, slightly organic, plastic clayfrom the Atchafalaya River Basin, LA

(Continued)

* East Atchafalaya Basin protection levee.

Table 6 (Concluded)

Material	Atterberg Limit, % LL	PL	PI	Description
Crushed limestone	--	--	--	Crushed limestone to be used as railroad ballast with particle sizes ranging from about 1 in. diam to rock floor. The amount of fine material is estimated to be about 10 percent
LSI-30 sand (SP)	--	--	--	A commercially available, washed, uniform California beach sand from near Monterey. Material is medium to fine and consists predominantly of quartz and feldspar particles
Enid Dam material (CL)	33	14	19	Dark-gray, silty clay consisting of silt- and clay-size particles of montmorillonite. Enid Dam is located in north-central Mississippi
Banding sand (F-75 sand) (SP)	--	--	--	Clean, fine, white quartz sand which is a specific gradation of Ottawa Silica sand with D_{50} = 0.2 mm and coefficient of uniformity 1.4
Wilmington Harbor material 72/2703 (OH)	133	53	80	Black, very organic clay from North Carolina with a large percentage of fibrous vegetable material and wood particles. Loss on ignition after two hours in an oven at 600° C was 36.7 percent of material mass by weight
Wilmington Harbor material 72/2697 (OH)	184	62	122	Gray heavy clay, OH, with a trace of sand and organic material
Lock and Dam 5 shale (CH)	69	24	45	Dark-gray, hard, massive clay shale with silt lenses from Lock and Dam 5 on the Red River near Shreveport, LA

Table 7

Summary of Microwave Tests and Controls

Soil	Initial Mass g	Drying Time* sec	Water Content % (1) Microwave Oven	Water Content % (2) Conventional Oven	Difference in Water Content** (1) - (2) %	Difference in Water Content** ((1) - (2))/(2) × (100) %
Vicksburg buckshot clay	1,161.74	1,620	22.11	22.27	-0.16	-0.72
	1,280.03	1,807	22.03	22.34	-0.31	-1.39
	1,162.43	1,780	23.96	23.93	0.03	0.13
	1,163.14	1,561	22.32	22.65	-0.33	-1.46
Boston blue clay	114.44	528^{I}	36.89	37.14	-0.25	-0.67
	139.35	373^{R}	31.92	31.98	-0.06	-0.19
	241.74	561^{R}	32.60	32.57	0.03	0.09
	247.10	589^{I}	28.29	28.10	0.19	0.68
San Francisco Bay mud	19.49	341	88.34	90.28	-1.94	-2.15
	39.77	434	90.38	89.57	0.81	0.90
	81.10	499	88.37	88.53	-0.16	-0.18
	160.20	803	89.13	89.32	-0.19	-0.21
	163.00	807	90.85	90.55	0.30	0.33
Vicksburg loess	164.80	530	18.58	18.90	-0.32	-1.69
	70.57	372	19.12	19.31	-0.19	-0.98
	35.24	403	18.51	19.10	-0.59	-3.08
Vicksburg loess and concrete sand	249.20	436	8.31	8.51	-0.20	-2.35
	284.30	435	8.11	8.34	-0.23	-2.76
Aquagel	140.12	1,175	461.85	463.67	-1.82	-0.39
	70.38	927	485.83	489.99	-4.16	-0.85
	35.14	774	494.91	488.28	6.63	1.36
Georgia kaolin	185.23	653	18.97	19.01	-0.04	-0.21
	172.92	683	50.57	50.72	-0.15	-0.30
EABPL clay	184.73	561	39.77	39.61	0.16	0.40
	160.90	871	68.45	68.67	-0.22	-0.32
LSI-30 sand	154.90	969	7.55	7.55	0.0	0.0
Crushed limestone	275.64	218	2.07	2.11	-0.04	-1.90

(Continued)

* I = intact or undisturbed specimen, R = remolded specimen.

** (1) = percent value from Microwave Oven column, (2) = percent value from Conventional Oven column.

Table 7 (Concluded)

Soil	Initial Mass g	Drying Time sec	Water Content % (1) Microwave Oven	Water Content % (2) Conventional Oven	Difference in Water Content (1) - (2) %	Difference in Water Content ((1) - (2))/(2) × (100) %
Enid Dam soil	209.47	558	22.35	22.48	-0.13	-0.58
	174.99	496	16.26	16.75	-0.49	-2.92
Banding sand	176.30	440	10.00	10.00	0.0	0.0
Wilmington Harbor material 72/7203	132.87	1,521	257.68	262.58	4.90	-1.86
Wilmington Harbor material 72/2697	120.95	996	91.14	91.07	0.07	0.08
Lock and Dam 5 shale	169.53	372	17.46	17.36	0.10	0.58
	437.94	744	18.94	18.74	0.20	1.07

Table 8

Summary of Data Comparing Effect of Soil Particle Size in Microwave Drying

Particle Size	Water Content %		Difference in Water Content	
	(1) Microwave Oven	(2) Conventional Oven	(1) - (2) %	((1) - (2))/ (2) × (100) %
4-in.-diam by 4-in.-high cylinder	22.11	22.27	-0.16	-0.72
	22.03	22.34	-0.31	-1.39
Roughly 1.5-in.-diam spheres	22.32	22.65	-0.33	-1.45
Roughly 0.1-in.-diam granules	23.96	23.93	+0.03	+0.13

Table 9

Summary of Data Comparing Effect of Specimen Mass in Microwave Drying

Soil	Normal Initial Mass, g	Drying Time sec	Water Content % (1) Microwave Oven	Water Content % (2) Conventional Oven	Difference in Water Content (1) - (2) %	Difference in Water Content ((1) - (2))/(2) × (100) %
San Francisco Bay mud	20	341	88.34	90.28	-1.94	-2.15
	40	434	90.38	89.57	0.81	0.90
	80	499	88.37	88.53	-0.16	-0.18
	160	803	89.13	89.32	-0.19	-0.21
	160	807	90.85	90.55	0.30	0.33
Aquagel	35	774	494.91	488.28	6.63	1.36
	70	927	485.83	489.99	-4.16	-0.85
	140	1,175	461.85	463.67	-1.82	-0.39
Vicksburg silty clay	35	403	18.51	19.10	-0.59	-3.08
	70	372	19.12	19.31	-0.19	-0.98
	165	530	18.58	18.90	-0.32	-1.69

APPENDIX A: COMPUTER CODE

```
4 PRINT"{CLR}"
5 INPUT"HIT RETURN TO CONTINUE";E$
8 POKE 808,39:POKE809,254
10 WO=0:TW=0:W=0:WN=0:F2%=0:TT=0
20 PRINT"{CLR}"
30 GOSUB3000
40 FOR J=1 TO 1000: NEXT J: REM DELAY
50 PRINT "MICROWAVE OVEN PROGRAM"
60 PRINT "INITIALIZING:STANDBY"
70 OPEN 2,2,0,CHR$(7+32)+CHR$(32+64)
71 GOSUB 6000
72 DIM A$(17): REM DIMENSION A$
75 GOSUB 5000
78 IF FLAG=1 THEN GOTO 100
80 FOR J=1 TO 1000: NEXT J: REM DELAY
90 PRINT#2,"P":REM SCALE POWER ON
100 FOR J=1 TO 5000: NEXT J: REM DELAY
110 PRINT#2,"R":REM RESET SCALE
120 FOR J=1 TO 1000: NEXT J: REM DELAY
140 GOSUB2000: REM READ ZERO
150 IF F<>0 THEN GOTO110
160 PRINT"{CLR}"
170 PRINT"PLACE TARE ON SCALE"
180 INPUT"PRESS ANY KEY AND RETURN";E$
190 IF E$="" THEN180
200 GOSUB2000: REM GO AND READ TARE
210 TW=W
220 TARE=(INT(TW*100))/100
230 PRINT"{CLR}"
240 PRINT"FILL TARE WITH 100-200"
250 PRINT"GRAMS OF MOIST SOIL, PLACE"
260 INPUT"ON PAN, PRESS ANY KEY AND RETURN";E$
270 IF E$="" THEN260
275 FORJ=1 TO 500:NEXTJ
280 GOSUB2000: REM READ INITIAL WEIGHT
292 IF F%=0 GOTO 300
295 OPEN4,4
296 IF F2%=1 THEN GOSUB 7000
297 PRINT#4,"TARE WEIGHT = "; TARE
300 WXYZ=W
305 PRINT"TARE WEIGHT = ", TARE
310 WETW=(INT(WXYZ*100))/100
320 PRINT"WET WEIGHT = ",WETW
322 IF F2%=0 GOTO 330
325 PRINT#4,"WET WEIGHT = ";WETW
327 REM IF F2%=1 THEN GOSUB 7100
330 GOSUB3000
340 MW=56577:CL=16:I=0:NI=24:RS=58
```

```
350 POKE MW,CL:FOR J=1 TO 100: NEXT J
360 POKE MW,RS:FOR J=1 TO 100: NEXT J
370 POKE MW,T:FOR J=1 TO 100: NEXT J
380 POKE MW,RS:FOR J=1 TO 100: NEXT J
390 FOR K=1 TO 4
400 POKE MW,NI:FOR J=1 TO 100: NEXT J
410 POKE MW,RS:FOR J=1 TO 100: NEXT J
420 NEXT K
430 INPUT"CLOSE DOOR, PRESS ANY KEY AND RETURN";E$
440 IF E$="" THEN430
443 PRINT"{CLR}"
445 GOSUB 7095
450 GOSUB2000
460 ABCD=W
470 OFFSET=WXYZ-ABCD
480 TUVW=ABCD+OFFSET
500 MW=56577:SR=32:RS=56
510 POKE MW,SR:FOR J=1 TO 100. NEXT J
520 POKE MW,RS:FOR J=1 TO 100: NEXT J
530 L=0
540 N=1
550 G0=0
560 TI$="000000"
570 X=VAL(TI$):IF X<30 THEN570
580 IF N=1 THEN W0=TUVW
590 GOSUB2000: REM GET WEIGHT
600 WN=W
610 G=((W0-TW)↑2-(WN-TW)↑2)/60
620 WC=((TUVW-WN)/(WN-TW))*100
630 G=(INT(G*10000))/10000
640 WN=(INT(WN*100))/100
650 WC=(INT(WC*1000))/1000
651 TT=TT+VAL(TI$)
652 IF F2%=0 THEN GOTO 660
655 PRINT#4,TT;CHR$(16)CHR$(49)CHR$(54):WN;CHR$(16)CHR$(51)CHR$(50);WC
660 PRINT TT;TAB(16);WN;TAB(30);WC
670 N=N+1
680 W0=WN
690 IF G=0 AND N=4 THEN 4000
700 IF G<G0 AND L=1 THEN GOTO740
710 IF G>=G0 THEN G0=G:GOTO560
720 IF G<G0 THEN L=1: GOTO560
740 MW=56577:SP=8:RS=56
750 POKE MW,SP:FOR J= 1 TO 100: NEXT J
760 POKE MW,RS:FOR J=1 TO 100: NEXT J
770 GOSUB2000
780 WN=W
790 MW=56577: SR=32: RS=56
800 POKE MW,SR:FOR J=1 TO 100: NEXT J
810 POKE MW,RS:FOR J=1 TO 100: NEXT J
820 TI$="000000"
830 X=VAL(TI$):IF X<30 THEN830
840 W0=WN
850 GOSUB2000
```

```
860 WN=W
870 WC=((TUVW-WN)/(WN-TW))*100
880 DW=(TUVW-TW)*(1/(WN-TW)-(1/(WO-TW)))
890 DW=(INT(DW*10000000))/10000000
900 WN=(INT(WN*100))/100
910 WC=(INT(WC*1000))/1000
911 TT=TT+VAL(TI$)
912 IF F2%=0 THEN GOTO 920
915 PRINT#4,TT;CHR$(16)CHR$(49)CHR$(54);WN;CHR$(16)CHR$(51)CHR$(50);WC
920 PRINT TT;TAB(16);WN;TAB(30);WC
930 IF DW>.02 THEN820
940 MW=56577: SP=8: RS=56
950 POKE MW,SP:FOR J=1 TO 100:NEXT J
960 POKE MW,RS:FOR J=1 TO 100:NEXT J
970 WO=WN
980 TI$="000000"
990 X=VAL(TI$):IF X<30 THEN990
1000 POKE MW,SR:FOR J=1 TO 100:NEXT J
1010 POKE MW,RS:FOR J=1 TO 100: NEXT J
1020 TI$="000000"
1030 X=VAL(TI$):IF X<30 THEN1030
1040 GOSUB2000
1050 WN=W
1060 WC=((TUVW-WN)/(WN-TW))*100
1070 DW=(TUVW-TW)*(1/(WN-TW)-(1/(WO-TW)))
1080 DW=(INT(DW*10000000))/10000000
1090 WN=(INT(WN*100))/100
1100 WC=(INT(WC*1000))/1000
1101 TT=TT+VAL(TI$)
1102 IF F2%=0 THEN GOTO 1110
1105 PRINT#4,TT;CHR$(16)CHR$(49)CHR$(54);WN;CHR$(16)CHR$(51)CHR$(50);WC
1110 PRINT TT;TAB(16);WN;TAB(30);WC
1120 IF DW>F1 THEN GOTO950
1130 MW=56577: SP=8: RS=56
1140 POKE MW,SP:FOR J= 1 TO 100:NEXT J
1150 POKE MW,RS:FOR J=1 TO 100:NEXT J
1160 TI$="000000"
1170 X=VAL(TI$): IF X<180 THEN1170
1180 GOSUB2000
1190 WN=W
1200 FOR K=1 TO 25
1210 POKE MW,CL:FOR J=1 TO 100:NEXT J
1220 POKE MW,RS:FOR J=1 TO 100:NEXT J
1230 NEXT K
1240 Z=((TUVW-WN)/(WN-TW))*100
1250 Z=(INT(Z*100)/100)
1252 IF F2%=0 THEN GOTO 1265
1255 PRINT#4,"WATER CONTENT =";Z;"%"
1260 PRINT#4,"FINAL WEIGHT =";WN;"G"
1265 PRINT"WATER CONTENT =";Z;"%"
1270 PRINT"FINAL WEIGHT =";WN;"G"
```

```
1280 FOR J= 1 TO 5000:NEXT J
1290 MW=56577: CL=16: RS=56
1300 POKE MW,CL:FOR J=1 TO 100:NEXT J
1310 POKE MW,RS:FOR J=1 TO 100:NEXT J
1320 PRINT#2,"P":REM SCALE POWER OFF
1330 PRINT"TEST IS OVER!"
1340 PRINT"REMOVE CONTAINER"
1360 PRINT"CAUTION!-CONTAINER IS HOT"
1365 CLOSE4
1366 CLOSE2
1367 INPUT"PRESS RETURN TO RESET FOR NEXT TEST";E$
1368 GOTO 10
1370 END
2000 REM SUBROUTINE TO READ THE SCALE
2010 FOR J=1 TO 17:GET #2,A$(J):NEXTJ
2020 PRINT#2,"Q":FOR J=1 TO 500 :NEXT J
2030 FOR J=1 TO 17
2040 GET #2,A$(J)
2050 IF A$(J)="" THEN 2040
2060 NEXT J
2070 IF A$(I)=CHR$(103) THEN A$(I)=CHR$(71)
2080 B$=A$(1)+A$(2)
2090 DT$=A$(5)+A$(6)+A$(7)+A$(8)+A$(9)+A$(10)+A$(11)+A$(12)+A$(13)
2100 IF B$="US" THEN GO TO 2020
2105 F=VAL(DT$)
2110 W=1.000*F
2120 RETURN
3000 REM SUBROUTINE TO INITIALIZE
3010 REM I/O PORT FOR MICROWAVE
3020 REM OVEN CONTROL
3030 Y=PEEK(56579)
3040 Y=Y OR 56
3050 POKE 56579,Y
3060 POKE 56579, 56
3070 POKE 56577,8
3080 FOR J=1 TO 100:NEXT J
3090 POKE 56577,56
3100 RETURN
4000 PRINT "SPECIMEN IS NOT"
4010 PRINT "LOSING WEIGHT."
4020 PRINT "CHECK SYSTEM"
4030 PRINT "AND RESTART."
4040 PRINT#2,"P":REM SCALE POWER OFF
4050 END
5000 PRINT#2,"Q":FOR J=1 TO 50: NEXT J
5010 FOR J=1 TO 17
5020 GET#2,A$(J)
5030 IF A$(J)<>"" THEN FLAG=1
5040 NEXT J
```

```
5050 RETURN
6000 REM OPERATOR INPUT
6010 INPUT"PLEASE INPUT DATE OF TEST";D$
6020 INPUT"WHAT IS THE PROJECT NUMBER?";P$
6030 INPUT"WHAT IS THE JOB NUMBER?";J$
6040 INPUT"IS THIS A CLEAN SAND?";I$
6045 F1=.002
6050 IF I$="Y" THEN F1=.0000:GOTO 6080
6060 IF I$<>"N" THEN GOTO 6040
6080 INPUT"ARE YOU USING A PRINTER?";I$
6085 F2%=0
6090 IF I$="Y" THEN F2%=1:GOTO 6110
6100 IF I$<>"N" THEN GOTO 6080
6110 RETURN
7000 REM HEADER INFO
7010 PRINT#4,"        MICROWAVE OVEN"
7020 PRINT#4," WATER CONTENT DETERMINATION"
7030 PRINT#4,"DATE: ";D$
7040 PRINT#4,"PROJECT NO: ";P$
7050 PRINT#4,"JOB NUMBER: ";J$
7065 REM HEADER INFO
7070 PRINT"        MICROWAVE OVEN"
7075 PRINT" WATER CONTENT DETERMINATION"
7077 PRINT"DATE: ";D$
7080 PRINT"PROJECT NO: ";P$
7085 PRINT"JOB NUMBER: ";J$
7090 RETURN
7095 IF F2%=0 THEN GOTO 7200
7100 PRINT#4,"TOTAL TIME      WET WEIGHT      WATER CONTENT"
7110 PRINT#4,"    SEC              G               %"
7120 PRINT#4,"------------     ------------     ----------------"
7130 PRINT#4," 0";CHR$(16)CHR$(49)CHR$(54);WETW;CHR$(16)CHR$(51)CHR$(50)" 
7200 PRINT"TOTAL TIME      WET WEIGHT      WATER"
7210 PRINT"    SEC              G               %"
7220 PRINT"------------     ------------     -------"
7230 PRINT " 0";TAB(16);WETW;TAB(31);"0"
7240 RETURN
```

APPENDIX B: TABLES OF SOIL DRYING DATA

The tables which will follow show time in the microwave oven versus weight change (water content) relationship for all tests performed. Time is in seconds, weight is in grams, and water content is computed as percent. At the end of the table, weight of the tare used and conventional oven water content are listed for comparison.

Table B1

Compacted Vicksburg Buckshot Clay Cylinder, Test 1

Time sec	Weight + Tare g	Water Content %
0	1,351.38	0.00
31	1,351.18	0.02
63	1,350.87	0.04
94	1,350.37	0.09
125	1,349.37	0.17
156	1,347.87	0.30
187	1,345.97	0.47
218	1,343.47	0.69
249	1,340.57	0.94
280	1,337.06	1.25
311	1,332.96	1.61
342	1,328.46	2.01
373	1,323.55	2.45
404	1,318.25	2.94
435	1,312.74	3.44
466	1,307.04	3.97
497	1,301.13	4.52
528	1,295.12	5.09
559	1,289.02	5.67
590	1,282.91	6.26
621	1,276.91	6.85
653	1,271.20	7.41
684	1,265.90	7.94
716	1,260.69	8.47
747	1,255.49	9.00
778	1,250.38	9.52
809	1,245.28	10.05
840	1,240.27	10.58
871	1,235.27	11.10
902	1,230.26	11.64
933	1,225.36	12.17
964	1,220.45	12.20
995	1,215.65	13.23
1,026	1,210.94	13.75
1,057	1,206.24	14.28

(Continued)

Table B1 (Concluded)

Time sec	Weight + Tare g	Water Content %
1,088	1,201.64	14.80
1,119	1,197.03	15.32
1,150	1,192.63	15.83
1,181	1,188.22	16.34
1,212	1,183.92	16.84
1,243	1,179.81	17.33
1,275	1,175.81	17.80
1,306	1,171.91	18.27
1,338	1,168.10	18.73
1,369	1,164.50	19.17
1,401	1,160.89	19.61
1,432	1,157.59	20.02
1,464	1,154.49	20.41
1,496	1,151.58	20.77
1,527	1,148.98	21.10
1,558	1,146.58	21.40
1,589	1,144.58	21.66
1,620	1,142.68	21.90
	Final weight = 1,140.97	
	Tare weight = 189.64	
	Conventional oven water content =	22.27

Table B2

Compacted Vicksburg Buckshot Clay Cylinder, Test 2

Time sec	Weight + Tare g	Water Content %
0	1,469.67	0.00
31	1,469.47	0.02
62	1,469.27	0.03
93	1,468.77	0.07
124	1,467.87	0.14
155	1,466.67	0.24
187	1,464.76	0.38
218	1,462.56	0.56
249	1,459.66	0.79
280	1,456.36	1.05
311	1,452.55	1.36
342	1,448.35	1.69
373	1,443.65	2.07
404	1,438.64	2.48
435	1,433.44	2.91
466	1,428.03	3.36
497	1,422.43	3.83
528	1,416.73	4.31
560	1,410.92	4.81
591	1,405.12	5.31
622	1,399.21	5.82
653	1,393.51	6.33
685	1,388.20	6.80
716	1,383.00	7.26
747	1,377.79	7.73
778	1,372.49	8.22
809	1,367.28	8.69
840	1,362.08	9.18
871	1,356.97	9.65
902	1,351.87	10.14
934	1,346.77	10.62
965	1,341.86	11.09
996	1,336.86	11.58
1,027	1,331.95	12.06
1,058	1,327.15	12.53

(Continued)

Table B2 (Concluded)

Time sec	Weight + Tare g	Water Content %
1,089	1,322.34	13.01
1,121	1,317.64	13.48
1,152	1,312.94	13.95
1,183	1,308.33	14.42
1,214	1,303.83	14.88
1,245	1,299.02	15.38
1,276	1,294.82	15.82
1,308	1,290.51	16.27
1,339	1,286.31	16.72
1,370	1,282.11	17.17
1,401	1,278.10	17.60
1,432	1,274.20	18.02
1,464	1,270.40	18.44
1,495	1,266.69	18.85
1,526	1,263.09	19.24
1,557	1,259.69	19.62
1,589	1,256.48	19.98
1,620	1,253.38	20.33
1,651	1,250.58	20.65
1,683	1,248.07	20.94
1,714	1,245.67	21.21
1,745	1,243.67	21.44
1,776	1,241.77	21.66
1,807	1,240.17	21.85
	Final weight = 1,238.57	22.03
	Tare weight = 189.64	
	Conventional oven water content =	22.34

Table B3

Vicksburg Buckshot Clay Granules

Time sec	Weight + Tare g	Water Content %
0	1,388.71	0.00
31	1,388.50	0.02
63	1,388.40	0.03
94	1,388.20	0.04
125	1,388.00	0.06
157	1,387.40	0.11
188	1,386.40	0.20
249	1,384.80	0.34
250	1,382.50	0.54
281	1,379.49	0.80
312	1,375.79	1.12
343	1,371.19	1.53
374	1,365.58	2.03
405	1,359.38	2.59
436	1,353.07	3.16
467	1,346.87	3.73
498	1,340.66	4.31
530	1,334.45	4.90
562	1,328.25	5.49
593	1,322.14	6.07
624	1,316.04	6.67
655	1,310.03	7.26
687	1,304.13	7.85
719	1,298.12	8.45
750	1,292.32	9.04
781	1,286.51	9.64
812	1,280.81	10.23
843	1,275.20	10.82
874	1,269.70	11.41
905	1,264.19	11.99
936	1,258.89	12.57
967	1,253.58	13.15
999	1,248.48	13.72
1,030	1,243.37	14.29
1,062	1,238.47	14.84

(Continued)

Table B3 (Concluded)

Time sec	Weight + Tare g	Water Content %
1,093	1,233.66	15.39
1,124	1,228.86	15.94
1,155	1,224.25	16.48
1,186	1,219.75	17.01
1,217	1,215.34	17.53
1,248	1,211.04	18.04
1,280	1,206.83	18.55
1,311	1,202.83	19.03
1,343	1,199.03	19.50
1,374	1,195.32	19.96
1,405	1,191.82	20.39
1,436	1,188.52	20.80
1,467	1,185.31	21.21
1,499	1,182.31	21.59
1,530	1,179.51	21.95
1,562	1,177.01	22.27
1,593	1,174.60	22.58
1,625	1,172.50	22.85
1,656	1,170.60	23.10
1,687	1,168.80	23.33
1,718	1,167.20	23.54
1,749	1,165.79	23.73
1,780	1,164.89	23.84
	Final weight = 1,163.99	23.96
	Tare weight = 226.28	
	Conventional oven water content =	23.93

Table B4

Compacted Vicksburg Buckshot Clay Chunks

Time sec	Weight + Tare g	Water Content %
0	1,352.58	0.00
32	1,352.57	0.00
63	1,352.27	0.03
94	1,351.67	0.08
125	1,350.67	0.16
156	1,348.87	0.32
187	1,346.37	0.54
218	1,343.06	0.82
249	1,339.16	1.17
281	1,334.66	1.56
312	1,329.55	2.02
343	1,323.95	2.52
374	1,318.14	3.05
405	1,312.13	3.60
436	1,305.93	4.18
467	1,299.72	4.76
498	1,293.22	5.38
530	1,286.81	5.99
560	1,280.41	6.62
591	1,273.00	7.35
623	1,266.69	7.97
654	1,260.69	8.58
685	1,255.08	9.15
716	1,249.58	9.72
747	1,244.17	10.28
779	1,238.77	10.85
810	1,233.56	11.40
842	1,228.36	11.96
873	1,223.35	12.50
904	1,218.45	13.04
935	1,213.54	13.58
966	1,208.64	14.13
998	1,203.73	14.68
1,029	1,198.93	15.22
1,061	1,194.22	15.76

(Continued)

Table B4 (Concluded)

Time sec	Weight + Tare g	Water Content %
1,092	1,189.62	16.30
1,123	1,185.21	16.81
1,154	1,180.81	17.33
1,185	1,176.60	17.83
1,216	1,172.60	18.31
1,248	1,168.20	18.78
1,279	1,164.88	19.25
1,311	1,161.29	19.69
1,342	1,157.99	20.10
1,373	1,154.88	20.48
1,404	1,151.98	20.85
1,436	1,149.38	21.17
1,467	1,147.17	21.45
1,499	1,145.27	21.69
1,530	1,143.57	21.91
1,561	1,142.07	22.10
	Final weight = 1,140.37	22.32
	Tare weight = 189.44	
	Conventional oven water content =	22.65

Table B5

Intact Boston Blue Clay

Time sec	Weight + Tare g	Water Content %
0	445.35	0.00
31	445.15	0.18
62	444.93	0.37
93	444.35	0.88
124	443.25	1.87
155	440.05	4.86
186	435.54	9.38
217	431.74	13.50
248	427.93	17.96
279	424.63	22.11
310	420.92	27.14
341	418.12	31.23
372	416.52	33.68
403	415.52	35.26
434	415.02	36.06
465	414.82	36.39
496	414.62	36.71
528	414.52	36.89
	Final weight = 414.52	36.89
	Tare weight = 330.91	
	Conventional oven water content =	37.14

Table B6

Remolded Boston Blue Clay, Test 1

Time sec	Weight + Tare g	Water Content %
0	236.97	0.00
31	234.69	1.67
63	229.99	5.28
94	219.27	14.55
125	214.77	18.95
156	210.76	23.17
187	207.76	26.53
218	205.66	28.99
249	204.45	30.45
280	203.75	31.31
311	203.45	31.68
342	203.35	31.80
374	203.25	31.92
	Final weight = 203.25	31.92
	Tare weight = 97.63	
	Conventional oven water content =	31.98

Table B7

Remolded Boston Blue Clay, Test 2

Time sec	Weight + Tare g	Water Content %
0	380.37	0.00
31	380.17	0.08
63	379.37	0.42
94	376.76	1.52
125	371.76	3.70
156	365.85	6.40
187	359.64	9.39
218	353.53	12.50
249	347.53	15.74
280	342.02	18.88
312	336.61	22.13
344	331.91	25.10
375	328.00	27.69
406	325.20	29.61
437	223.20	31.02
468	322.19	31.73
499	321.58	32.17
530	321.29	32.38
561	321.09	32.53
	Final weight = 320.99	32.60
	Tare weight = 138.63	
	Conventional oven water content =	32.57

Table B8

Shredded Boston Blue Clay

Time sec	Weight + Tare g	Water Content %
0	578.01	0.00
31	578.01	0.00
62	577.81	0.08
94	577.41	0.24
125	575.61	0.98
156	570.30	3.23
187	564.70	5.71
218	559.19	8.27
248	553.68	10.95
279	548.68	13.56
310	543.57	16.24
341	538.86	18.87
372	534.56	21.40
403	530.75	23.72
433	527.75	25.61
464	526.05	26.71
496	525.05	27.37
527	524.45	27.76
558	524.05	28.03
589	523.75	28.23
	Final weight = 323.65	28.29
	Tare weight = 331.50	
	Conventional oven water content =	28.10

Table B9

San Francisco Bay Mud, 20-g

Time sec	Weight + Tare g	Water Content %
0	177.42	0.00
31	177.02	2.11
63	175.02	14.11
94	173.02	29.30
125	171.31	45.91
156	169.91	63.05
187	169.21	73.23
218	168.71	81.32
249	168.51	84.77
280	168.41	86.54
311	168.31	88.35
341	168.31	88.34
	Final weight = 168.31	88.34
	Tare weight = 158.00	
	Conventional oven water content =	90.28

Table B10

San Francisco Bay Mud, 40-g

Time sec	Weight + Tare g	Water Content %
0	181.73	0.00
31	181.53	0.51
62	180.52	3.13
93	178.32	9.39
124	175.62	18.20
155	172.82	28.98
186	170.31	40.41
217	167.81	54.07
248	165.71	67.77
279	164.21	79.16
310	163.40	85.88
341	163.10	88.53
372	163.00	89.43
403	162.80	91.27
434	162.80	91.27
	Final weight = 162.90	90.38
	Tare weight = 142.08	
	Conventional oven water content =	89.57

Table B11

San Francisco Bay Mud, 80-g

Time sec	Weight + Tare g	Water Content %
0	219.57	0.00
31	219.37	0.25
62	217.07	3.18
93	213.77	7.71
125	209.36	14.41
156	205.24	21.47
187	201.55	28.57
219	197.95	36.37
250	194.64	44.39
281	191.44	53.12
313	188.54	62.00
344	185.73	71.61
375	183.63	79.60
406	182.43	84.51
437	181.83	87.07
468	181.63	87.94
499	181.53	88.37
	Final weight = 181.53	88.37
	Tare weight = 138.47	
	Conventional oven water content =	88.53

Table B12

San Francisco Bay Mud, 160-g

Time sec	Weight + Tare g	Water Content %
0	301.67	0.00
31	301.67	0.00
62	301.27	0.25
94	300.07	0.99
125	297.77	2.45
156	293.66	5.17
187	288.86	8.53
218	283.95	12.20
249	279.25	15.95
280	274.64	19.88
311	270.04	24.08
342	265.63	28.39
373	261.32	32.90
404	257.02	37.73
434	252.81	42.81
465	248.61	48.27
496	244.40	54.17
527	240.50	60.08
558	236.69	66.30
589	233.29	72.28
620	230.29	77.92
651	227.68	83.13
682	225.88	86.91
713	224.98	88.86
744	224.38	90.19
775	224.18	90.63
807	224.18	90.63
	Final weight = 224.08	90.85
	Tare weight = 138.67	
		Conventional oven water content = 90.55

Table B13

Vicksburg Loess, 165-g

Time sec	Weight + Tare g	Water Content %
0	262.43	0.00
31	262.33	0.06
62	262.23	0.12
93	259.22	1.98
124	255.52	4.38
155	252.31	6.54
186	249.41	8.58
217	246.71	10.54
248	244.80	11.97
280	243.00	13.36
311	241.50	14.54
342	240.20	15.59
374	239.20	16.41
406	238.30	17.15
437	237.70	17.65
468	237.19	18.08
499	236.89	18.33
530	236.69	18.50
	Final weight = 236.59	18.58
	Tare weight = 97.63	
	Conventional oven water content =	18.90

Table B14

Vicksburg Loess, 70-g

Time sec	Weight + Tare g	Water Content %
0	210.26	0.00
31	210.16	0.14
62	209.36	1.29
93	207.66	3.83
124	205.86	6.66
155	204.15	9.49
186	202.55	12.28
217	201.25	14.65
248	200.35	16.36
279	199.65	17.72
310	199.25	18.51
341	199.05	18.91
372	198.95	19.12
	Final weight = 198.95	19.12
	Tare weight = 139.76	
	Conventional oven water content =	19.31

Table B15

Vicksburg Loess, 35-g

Time sec	Weight + Tare g	Water Content %
0	86.31	0.00
31	86.31	0.00
62	86.21	0.29
93	85.71	1.73
124	84.71	4.76
155	83.91	7.31
186	83.11	9.99
217	82.51	12.09
248	82.01	13.90
279	81.61	15.39
310	81.31	16.54
341	81.11	17.31
372	80.81	18.51
403	80.81	18.51
	Final weight = 80.81	18.51
	Tare weight = 51.07	
	Conventional oven water content =	19.10

Table B16

Vicksburg Loess and Concrete Sand, Test 1

Time sec	Weight + Tare g	Water Content %
0	378.37	0.00
31	378.26	0.04
62	378.16	0.08
94	377.56	0.32
125	374.36	1.63
156	370.96	3.06
187	368.25	4.23
218	366.05	5.20
249	364.45	5.92
280	363.15	6.50
311	362.04	7.01
342	361.24	7.38
373	360.54	7.70
404	360.04	7.94
436	359.64	8.12
	Final weight = 359.25	8.31
	Tare weight = 129.17	
	Conventional oven water content =	8.51

Table B17

Vicksburg Loess and Concrete Sand, Test 2

Time sec	Weight + Tare g	Water Content %
0	423.03	0.00
32	422.92	0.04
63	422.82	0.07
94	422.32	0.25
125	418.71	1.54
156	414.81	2.97
187	411.51	4.22
218	408.90	5.23
249	407.00	5.97
280	405.60	6.53
311	404.50	6.97
342	403.70	7.29
373	403.00	7.58
404	402.47	7.78
435	402.09	7.95
	Final weight = 401.70	8.11
	Tare weight = 138.73	
	Conventional oven water content =	8.43

Table B18

Aquagel, 140-g

Time sec	Weight + Tare g	Water Content %
0	278.85	0.00
31	278.65	0.14
63	278.15	0.50
94	276.94	1.38
125	274.54	3.17
156	270.44	6.38
187	265.03	10.94
218	259.32	16.19
249	253.72	21.85
280	248.41	27.75
311	243.00	34.38
342	237.90	41.29
373	232.79	48.96
404	227.88	57.17
435	223.08	66.11
465	218.37	75.94
496	213.77	86.72
527	209.36	98.38
558	204.96	111.56
589	200.75	125.92
620	196.66	141.87
651	192.64	159.91
682	188.94	179.06
713	185.33	200.68
744	181.93	224.34
774	178.72	250.38
805	175.72	278.79
836	172.92	309.82
867	170.31	343.69
898	168.01	378.54
929	166.31	408.03
960	165.21	429.14
991	164.51	443.51
1,022	164.11	452.07
1,053	164.01	454.26

(Continued)

Table B18 (Concluded)

Time sec	Weight + Tare g	Water Content %
1,084	163.81	458.68
1,114	163.71	460.91
1,144	163.71	460.91
1,175	163.71	460.91
	Final weight = 163.67	461.85
	Tare weight = 138.73	
	Conventional oven water content =	463.67

Table B19

Aquagel, 70-g

Time sec	Weight + Tare g	Water Content %
0	168.11	0.00
31	167.91	0.28
63	167.21	1.30
94	165.61	3.68
125	161.70	10.02
156	157.50	17.75
186	153.39	26.44
218	149.59	35.71
249	145.98	45.86
280	142.58	56.92
311	139.38	68.97
342	136.17	83.08
373	133.27	98.02
403	130.36	115.68
434	127.66	135.13
465	125.06	157.50
496	122.56	183.42
527	120.05	215.28
558	117.75	251.50
588	115.55	294.88
619	113.54	345.07
650	112.14	388.30
681	111.24	420.82
712	110.64	445.02
743	110.24	462.44
774	110.04	471.58
804	109.84	481.01
834	109.84	481.01
865	109.74	485.85
896	109.64	490.77
927	109.74	485.83
	Final weight = 109.74	485.83
	Tare weight = 97.73	
	Conventional oven water content =	489.99

Table B20

Aquagel, 35-g

Time sec	Weight + Tare g	Water Content %
0	86.21	0.00
31	85.91	0.86
62	84.61	4.77
93	81.81	14.32
125	78.80	26.73
156	76.00	40.96
187	73.40	57.37
218	70.99	76.41
249	68.79	98.31
280	66.69	124.97
310	64.79	156.13
341	62.98	195.06
372	61.38	240.85
403	60.08	290.02
434	59.18	333.31
465	58.58	367.93
496	58.08	401.30
527	57.88	416.02
558	57.58	439.80
588	57.38	456.91
619	57.28	465.88
650	57.18	475.14
681	57.08	484.71
711	57.08	484.71
743	56.98	494.61
774	56.98	494.91
	Final weight = 56.98	494.91
	Tare weight = 51.07	
	Conventional oven water content =	488.28

Table B21

Georgia Kaolin, Test 1

Time sec	Weight + Tare g	Water Content %
0	282.85	0.00
31	282.75	0.05
63	282.65	0.11
94	281.85	0.54
126	278.45	2.44
157	275.04	4.40
188	271.94	6.26
219	269.23	7.94
250	266.73	9.53
281	264.53	10.98
312	262.63	12.26
343	261 02	13.36
374	259.72	14.27
405	258.52	15.12
436	257.52	15.84
467	256.62	16.50
498	255.82	17.09
529	255.12	17.61
560	254.52	18.06
591	254.02	18.44
622	253.61	18.74
653	253.41	18.90
	Final weight = 253.31	18.97
	Tare weight = 97.63	
	Conventional oven water content =	19.01

Table B22

Georgia Kaolin, Test 2

me ec	Weight + Tare g	Water Content %
0	270.54	0.00
31	270.44	0.05
62	270.13	0.23
93	268.03	1.47
24	262.63	4.79
55	257.12	8.41
86	251.91	12.07
17	246.71	15.98
48	241.60	20.10
79	236.49	24.52
10	231.59	29.07
41	227.28	33.36
72	223.48	37.39
03	220.37	40.87
34	217.87	43.80
65	216.07	45.98
96	214.77	47.60
27	213.87	48.74
58	213.37	49.39
89	212.97	49.90
20	212.76	50.18
52	212.66	50.31
83	212.46	50.57
	Final weight = 212.46	50.57
	Tare weight = 97.62	
	Conventional oven water content =	50.72

Table B23

EABPL Gray Clay, Test 1

Time sec	Weight + Tare g	Water Content %
0	323.40	0.00
31	323.20	0.11
62	322.10	0.71
94	318.70	2.61
125	312.69	6.16
156	306.48	10.08
188	300.67	14.03
219	295.27	17.96
250	290.36	21.78
281	286.06	25.33
312	282.45	28.48
343	279.25	31.41
374	276.74	33.80
405	274.74	35.76
436	273.14	37.38
467	272.14	38.41
498	271.54	39.03
529	271.14	39.45
561	270.94	39.66
	Final weight = 270.84	39.77
	Tare weight = 138.67	
	Conventional oven water content =	39.61

Table B24

EABPL Gray Clay, Test 2

Time sec	Weight + Tare g	Water Content %
0	258.52	0.00
31	258.42	0.06
62	258.02	0.31
93	255.62	1.84
125	250.11	5.52
156	244.50	9.54
187	239.20	13.65
218	233.99	17.99
250	228.88	22.58
281	223.98	27.34
312	219.27	32.26
343	214.87	37.23
375	210.86	42.09
406	207.36	46.62
437	204.35	50.75
468	201.85	54.37
499	199.75	57.55
530	198.15	60.06
561	196.85	62.16
592	195.84	63.81
623	195.04	65.16
654	194.44	66.18
685	194.14	66.70
716	193.84	67.22
747	193.54	67.74
778	193.44	67.92
809	193.34	68.10
840	193.24	68.27
871	193.14	68.45
	Final weight = 193.14	68.45
	Tare weight = 97.62	
		Conventional oven water content = 68.67

Table B25

LSI-30 Sand, Test 1

Time sec	Weight + Tare g	Water Content %
0	355.04	0.00
31	355.04	0.00
62	354.94	0.05
93	354.73	0.14
124	354.23	0.37
155	353.03	0.94
186	351.63	1.61
217	350.33	2.24
248	349.13	2.82
279	348.23	3.27
310	347.33	3.72
341	346.62	4.07
372	346.02	4.37
403	345.52	4.63
434	345.02	4.88
465	344.52	5.14
496	344.12	5.34
527	343.62	5.60
558	343.36	5.76
589	342.73	6.07
620	342.53	6.17
651	342.43	6.22
682	342.33	6.27
713	342.23	6.32
744	341.93	6.47
775	341.63	6.62
806	341.43	6.72
837	341.23	6.82
868	341.03	6.92
899	340.83	7.02
930	340.63	7.12
961	340.53	7.17
992	340.33	7.27
1,023	340.33	7.27
	Final weight = 340.23	7.37
	Tare weight = 140.48	
		Conventional oven water content = 7.56

Table B26

LSI-30 Sand, Test 2

Time sec	Weight + Tare g	Water Content %
0	355.14	0.00
31	355.04	0.05
62	354.94	0.09
93	354.84	0.14
124	354.23	0.42
155	352.93	1.03
186	351.53	1.70
217	350.33	2.28
248	349.23	2.82
279	348.33	3.27
310	347.53	3.66
342	346.72	4.07
373	346.12	4.37
405	345.52	4.67
436	344.92	4.98
468	344.42	5.24
499	344.02	5.44
531	343.52	5.70
562	343.12	5.91
593	342.72	6.12
624	342.42	6.28
655	342.02	6.49
686	341.82	6.59
717	341.52	6.75
749	341.22	6.91
780	341.02	7.02
811	340.82	7.13
843	340.62	7.23
874	340.42	7.34
905	340.32	7.39
938	340.12	7.50
969	340.12	7.50
	Final weight = 340.02	7.55
	Tare weight = 139.85	
	Conventional oven water content =	7.55

Table B27

Crushed Limestone

Time sec	Weight + Tare g	Water Content %
0	414.31	0.00
31	414.11	0.07
62	413.91	0.15
93	412.91	0.51
124	411.31	1.10
155	410.11	1.55
186	409.41	1.81
218	408.91	2.00
	Final weight = 408.71	2.07
	Tare weight = 138.67	
	Conventional oven water content =	2.11

Table B28

Enid Dam Material, Test 1

Time sec	Weight + Tare g	Water Content %
0	351.38	0.00
31	351.28	0.05
62	351.18	0.10
93	350.28	0.53
124	345.89	2.69
155	340.79	5.33
186	335.69	8.10
217	331.20	10.67
248	327.20	13.05
279	323.90	15.10
310	321.20	16.83
341	319.10	18.21
372	317.40	19.36
403	316.11	20.25
434	315.11	20.95
465	314.31	21.51
496	313.81	21.86
527	313.51	22.07
558	313.31	22.22
	Final weight = 313.11	22.35
	Tare weight = 141.91	
	Conventional oven water content =	22.48

Table B29

Enid Dam Material, Test 2

Time sec	Weight + Tare g	Water Content %
0	273.03	0.00
31	273.03	0.00
62	272.83	0.11
93	269.43	2.10
124	265.44	4.54
155	262.04	6.70
186	259.14	8.62
217	256.84	10.20
248	254.94	11.53
279	253.44	12.60
310	252.24	13.48
341	251.34	14.15
372	250.54	14.74
403	249.84	15.27
434	249.35	15.65
465	248.95	15.96
496	248.75	16.11
	Final weight = 248.55	16.26
	Tare weight = 98.04	
	Conventional oven water content =	16.75

Table B30

Banding Sand (F-75 Sand)

Time sec	Weight + Tare g	Water Content %
0	287.60	0.00
32	287.50	0.06
64	285.89	0.97
96	282.50	2.98
128	279.50	4.82
160	276.89	6.46
192	275.00	7.70
223	273.70	8.56
254	273.00	9.03
285	272.39	9.44
316	272.00	9.71
347	271.79	9.84
378	271.60	9.98
409	271.50	10.00
440	271.50	10.00
	Final weight = 271.50	10.00
	Tare weight = 111.30	
	Conventional oven water content =	10.00

Table B31

Wilmington Harbor 72/2703 Material

Time sec	Weight + Tare g	Water Content %
0	290.06	0.00
31	289.95	0.08
63	289.55	0.38
94	287.65	1.84
125	283.15	5.48
156	277.44	10.49
187	271.63	16.10
218	266.02	22.08
249	260.72	28.34
280	255.61	35.00
311	250.41	42.54
343	245.30	50.80
373	240.19	60.07
40[illegible]	235.29	70.13
435	230.78	80.55
466	226.58	91.49
497	222.77	102.60
528	219.47	113.35
559	216.46	124.16
590	213.96	134.04
621	211.56	144.39
652	209.46	154.22
682	207.65	163.30
713	205.95	172.49
744	204.65	179.96
775	203.35	187.86
806	202.25	194.89
838	201.35	200.91
868	200.54	206.47
899	199.84	211.51
930	199.14	216.71
961	198.64	220.53
992	198.09	225.25
1,023	197.64	228.47
1,054	197.34	230.93

(Continued)

Table B31 (Concluded)

Time sec	Weight + Tare g	Water Content %
1,085	196.94	234.26
1,116	196.54	237.66
1,147	196.34	239.39
1,178	195.94	242.90
1,209	195.64	245.58
1,240	195.44	247.39
1,272	195.24	249.21
1,304	195.14	250.14
1,335	194.94	251.99
1,366	194.84	252.93
1,397	194.74	253.87
1,428	194.64	254.82
1,459	194.54	255.77
1,490	194.44	256.72
1,521	194.44	256.72
	Final weight = 194.34	257.68
	Tare weight = 157.33	
	Conventional oven water content =	262.58

Table B32

Wilmington Harbor 72/2697 Material

Time sec	Weight + Tare g	Water Content %
0	279.24	0.00
31	279.14	0.08
63	278.84	0.33
94	276.74	2.11
125	272.13	6.24
156	267.03	11.23
187	261.82	16.83
218	256.71	22.89
249	252.01	29.06
281	242.70	35.27
312	244.00	41.12
343	240.89	46.42
374	238.19	51.38
405	235.79	56.07
436	233.58	60.64
466	231.68	64.80
497	229.98	68.72
528	228.58	72.08
559	227.28	75.32
590	226.28	77.91
621	225.37	80.30
652	224.67	82.20
683	223.87	84.43
714	223.37	85.85
745	222.97	86.99
776	222.67	87.87
807	222.37	88.75
839	222.17	89.34
870	221.97	89.94
902	221.87	90.24
933	221.77	90.54
965	221.67	90.84
996	221.67	90.84
	Final weight = 221.57	91.14
	Tare weight = 158.29	

Conventional oven water content = 91.07

Table B33

Lock and Dam 5 Shale, Test 1

Time sec	Weight + Tare g	Water Content %
0	318.50	0.00
31	318.40	0.06
62	317.00	0.89
93	313.21	3.23
124	308.61	6.20
155	304.01	9.35
186	300.31	12.03
217	297.42	14.22
248	295.62	15.62
279	294.42	16.57
310	293.82	17.06
341	293.52	17.30
372	293.42	17.38
	Final weight = 293.32	17.46
	Tare weight = 148.97	
	Conventional oven water content =	17.36

Table B34

Lock and Dam 5 Shale, Test 2

Time sec	Weight + Tare g	Water Content %
0	681.39	0.00
31	681.19	0.05
62	680.99	0.09
93	680.49	0.21
124	679.29	0.48
155	676.59	1.11
186	671.99	2.19
217	666.79	3.45
248	661.70	4.71
279	656.70	5.97
310	652.00	7.19
341	647.71	8.33
372	643.41	9.50
403	639.31	10.63
434	635.31	11.58
465	631.62	12.82
496	627.92	13.91
527	624.52	14.92
558	621.42	15.86
589	618.72	16.70
620	616.52	17.39
651	614.73	17.95
682	613.63	18.30
713	612.73	18.59
744	612.13	18.79
	Final weight = 611.63	18.94
	Tare weight = 243.45	
	Conventional oven water content =	18.74